CHEMICAL STABILISATION OF
WHAKA TERRACE LOESS
CHRISTCHURCH

A thesis

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ABSTRACT

The dispersive and erodible nature of some loess soils on the Port Hills results in a variety of mass movement, surface and sub-surface erosion features. These features produce engineering problems for residential development, and chemical stabilisation techniques have been used to reduce and/or prevent further erosion by rendering the soils non-dispersive and non-erodible.

Field and laboratory investigations were undertaken to characterise the dispersive and erodible nature of Whaka Terrace subdivision loess, as well as to assess changes in chemistry and mineralogy of the chemically stabilised soils. Field investigation included engineering geological mapping, geophysical surveying, hand auger hole drilling and logging, and sampling.

The application of 1%, 2%, and 4% hydrated lime, quicklime, Portland cement, gypsum, and a mixture of hydrated lime and gypsum (on a 1:1 basis) was used to stabilise erodible loess-colluvium in the laboratory. Evaluation tests included permeability, pinhole erodibility, jar slaking, uniaxial swelling, crumb dispersion, unconfined compressive strength, undrained shear strength, and the determination of optimum moisture content, Atterberg limits and grainsize distribution. Soil chemistry was analysed using $_{p}H$, soluble salts, organic content, cation exchange capacity and XRF, while XRD, SEM and EDAX were used to study soil mineralogy and fabric.

Application of 1 and 2% quicklime and hydrated lime produces a non-erodible, non-dispersive and durable material which resists slaking and swelling during saturation, and wetting and drying cycles. Application of Portland cement at higher concentration (2 and 4%) produces similar results to that of hydrated lime and quicklime, while gypsum fails to produce a non-erodible and durable material. Furthermore, although the application of a mixed hydrated lime and gypsum stabiliser produces a non-dispersive and non-erodible material, it fails to produce a durable material and mixed stabiliser soils possess a high potential for swelling and slaking.

The unconfined compressive strength and shear strength of all stabilised samples except gypsum increases by 2-3 times relative to the untreated samples. This increase in strength is related to the production of pozzolanic cementing agents (pozzolanic reaction) in the chemically stabilised samples. The presence of cementing agents also changes the strain deformation of treated samples by producing a more brittle material relative to the untreated samples.

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CHAPTER ONE : INTRODUCTION

1.1 Project Background

Banks Peninsula consists of the eroded calderas of the Lyttelton and Akaroa volcanoes, which were active in Miocene times and which are now mantled by aeolian quartzofeldspathic loess deposits of Quarternary age. The dispersive and erosive nature of some loess soils produces a variety of engineering problems for residential development on the lower slopes of the Port Hills (Fig 1.1). Whaka Terrace (Fig 1.2) is a subdivision which displays a variety of mass movement and erosion features, particularly tunnel gully development as well as rill and sheet erosion on unvegetated and disturbed ground. The testing programme described in this thesis has been confined to soils from Whaka Terrace.

Chemical stabilisation techniques, especially the use of hydrated lime, have been used successfully to overcome erosion problems by rendering loess soils non-dispersive and non-erodible. However, the extent of previous research in some areas is limited, and this project has involved further investigation of properties of stabilised soils with respect to shear strength, chemistry and mineralogy. In addition, until now chemical stabilisation of the Port Hills loess has been dominated by the use of hydrated lime, and there is a need to assess the usefulness of alternative stabilising agents, such as Portland cement, quicklime, gypsum, and a mixture of hydrated lime and gypsum.

1.2. Principles of Chemical Stabilisation

Chemical stabilisation techniques have been widely used to alter or enhance specific engineering properties of natural soils. Ingles and Metcalf (1972) have suggested that the main properties of a soil which should be considered in an engineering construction project are:

a) durability
b) volume stability
c) strength
d) permeability

Of these factors, the first three are considered to have the greatest relevance to subdivision planning on the Port Hills, and considered in more detail in Chapters 2 and 3, in relation to loess deposits.

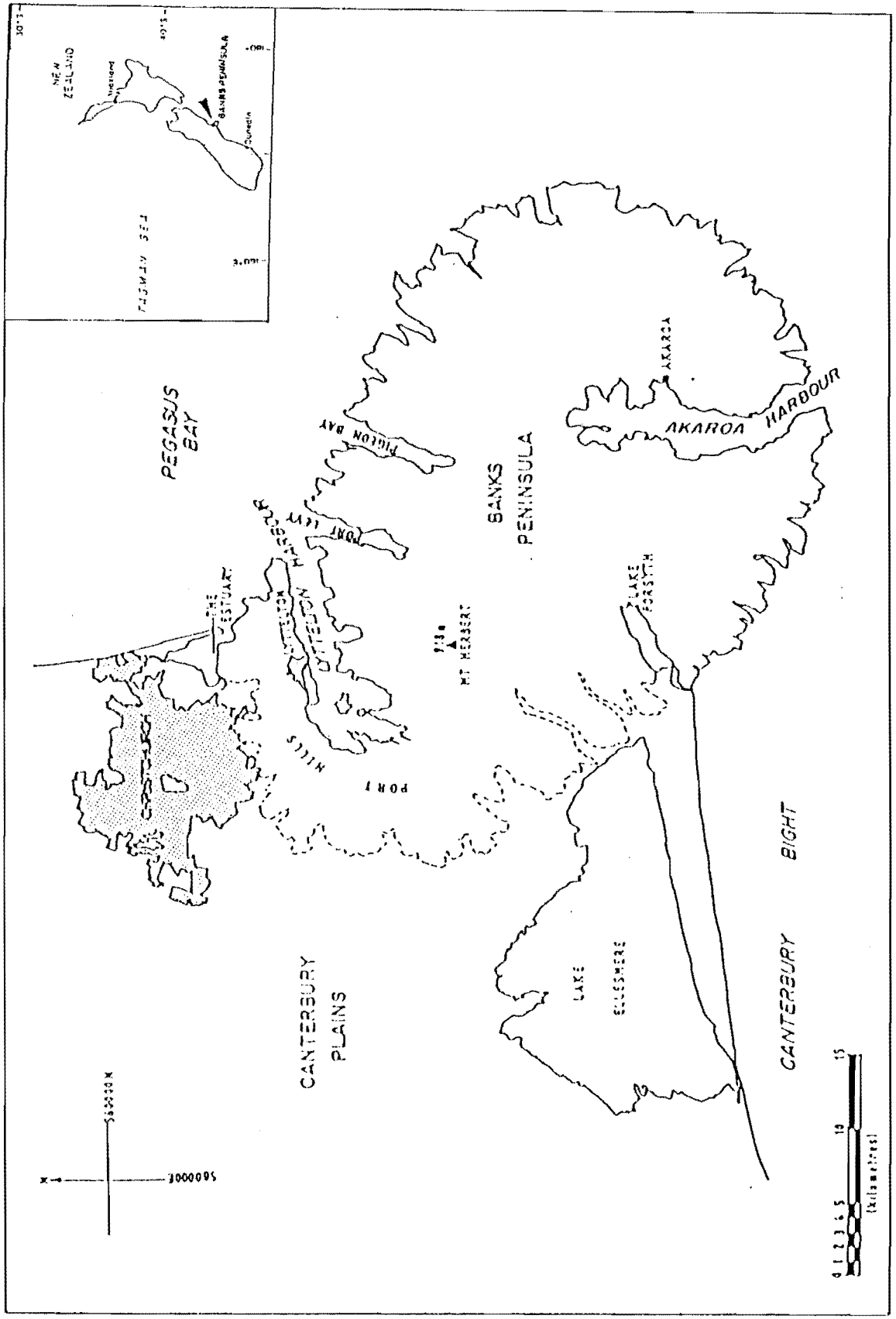


Fig. 1.1 Banks Peninsula location map.

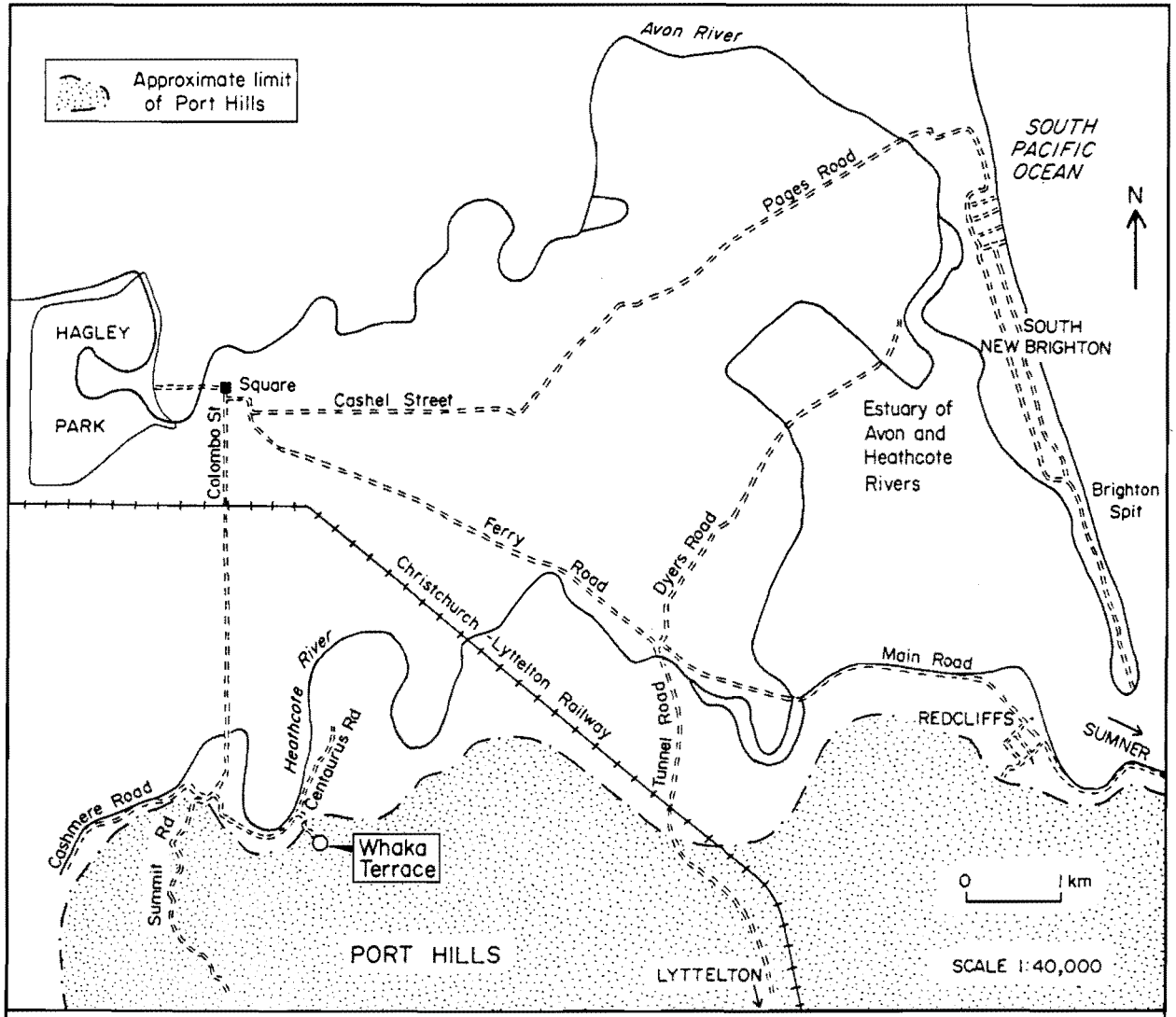


Figure 1.2 Location diagram for Whaka Terrace

1.2.1. Durability

Generally durability refers to the resistance of soil or rock material to short-term weathering, although in this study durability is considered mainly as the resistance of soil material to erosion and dispersion processes as related to the action of running or infiltrating water. Research by Evans (1977) has indicated that some loess soils on the Port Hills have a high potential for dispersion and erosion. These properties of some loess soil provides a number of difficulties for engineering works and urban development on the Port Hills (Fig 1.3 and 1.4).

1.2.2. Volume Instability

Due to seasonal fluctuation of moisture content and temperature, shrinkage and swelling are seen in many soils. This process is commonly referred to as volume instability, and is widely regarded as being responsible for damage to house foundation and road structures on the Port Hills. Miller (1971) illustrated that shrinkage is the primary factor in allowing access of water to potentially dispersive and erosive subsoils, leading to tunnel gully formation. Fig 1.5 illustrates the relationship between shrinkage and tunnel gully formation.

1.2.3. Strength

Soil strength is a measure of the ability of the soil skeleton to resist deformation resulting from normal or shear forces. Inadequate strength or deformation resistance leads to problems such as bearing capacity failure in roads and foundations of structures, as well as slope instability on hill sides. On the Port Hills, areas of lower shear strength are commonly associated with seepage zones where loess soils are saturated and /or softened. Such areas can commonly be identified by the presence of hummocky ground on the slopes (Fig 1.6).

In conclusion, the use of chemical stabilisers in dispersive and erosive loessial soils on the Port Hills is to alter the soil mass to a more rigid or granular material in which particles are strongly bonded together, thereby improving such properties as shrink / swell behavior, strength and deformation characteristics, and resistance to erosion and weathering processes.

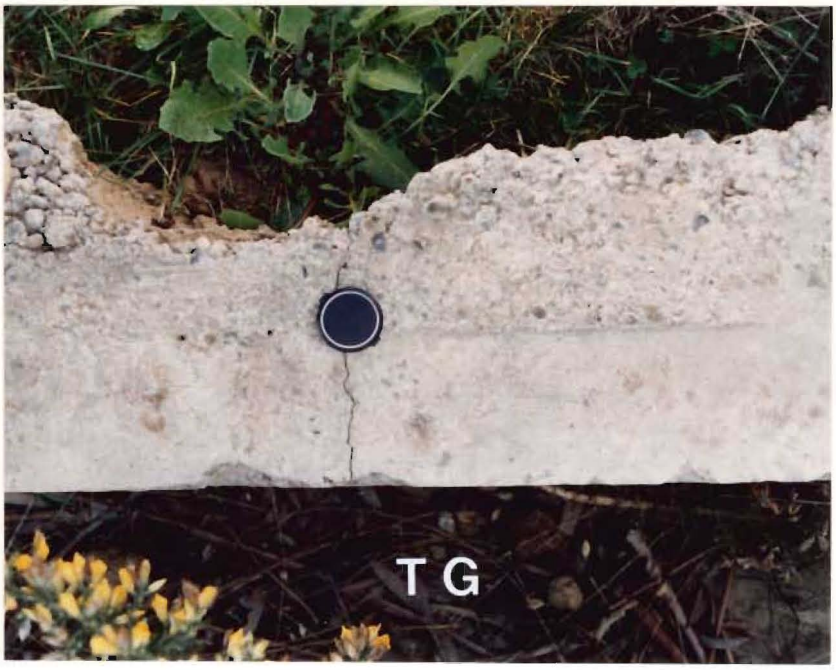


Fig. 1.3 Crack in concrete kerb due to lack of support underneath. Note location of tunnel gully (TG).

Fig. 1.4 Service trench failure after backfilling with erodible loess (trench acts as channel-way for water flows). (from Bell, 1981 a)

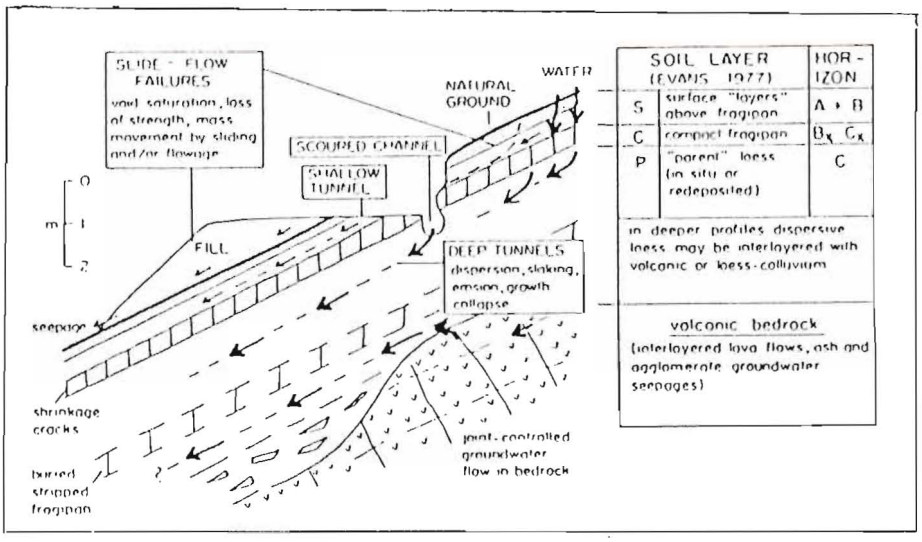


Fig. 1.5 General slope failure model. Note shrinkage cracks and tunnelling.
(after Evans & Bell, 1981).

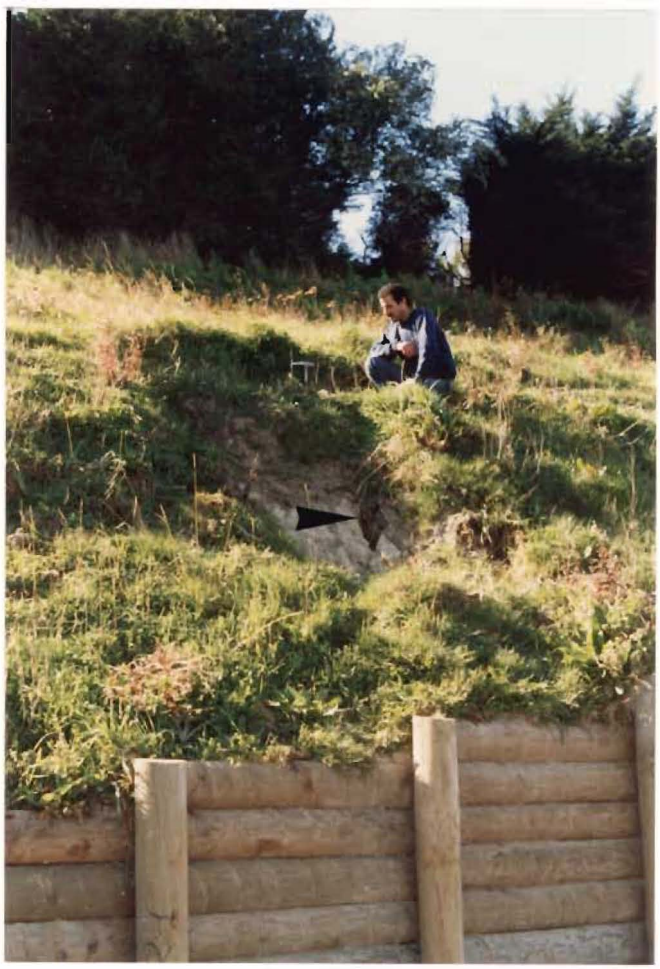


Fig. 1.6 Slope movement at Whaka Terrace. Note the scarp and hummocky ground above the retaining wall, (also note exit of tunnel gully).

1.3. Study Objectives

This project has been undertaken with the following aims:

1) To review the effect of hydrated lime on Port Hills loess in order to verify the results of earlier studies, as well as to broaden the knowledge in areas about which information is incomplete.

2) To assess the potential of those stabiliser agents which have similar Ca^{+2} cation availability to hydrated lime, such as Portland cement, quicklime, gypsum and a mixture of gypsum and hydrated lime (1:1 ratio).

1.4. Previous Work

1.4.1. Geology

1) Bedrock Geology

Banks Peninsula consists of the eroded calderas of the Lyttelton and Akaroa Volcanoes, which are composed of rubbly and massive aa - type basaltic and andesitic lavas, pyroclastics deposits, lahars and dykes (Weaver et al 1985). The Lyttelton Volcano was erupted on the older basement rocks, which consist of Triassic age greywacke and argillite strata of the Torlesse Group which are exposed in the Gebbies Pass area, and younger Miocene age basement rocks consisting of Gebbies Rhyolite belonging to the Governors Bay Volcanics. The simplified geology of Banks Peninsula is shown in Fig 1.7.

The Lyttelton and Akaroa volcanic activity ceased during the Pliocene and was followed by the establishment of a typical radial drainage pattern on the flanks of the volcanoes. The Lyttelton and Akaroa volcanoes were developed initially as an island on the western end of the Chatham Rise. However, the deposition of gravel outwash fans from the southern Alps during the Pleistocene connected the north-western part of the island to the mainland, forming the Canterbury Plains and Banks Peninsula (Liggett and Gregg, 1965).

2) Loess Deposits

During late Pleistocene glaciation of Southern Alps predominantly silt size material (derived from the grinding action of glacial processes) was wind blown across the Canterbury Plains, and deposited as a blanket over the irregular slopes of Banks Peninsula (Fig 1.8). Many of these loess deposits were subsequently eroded and

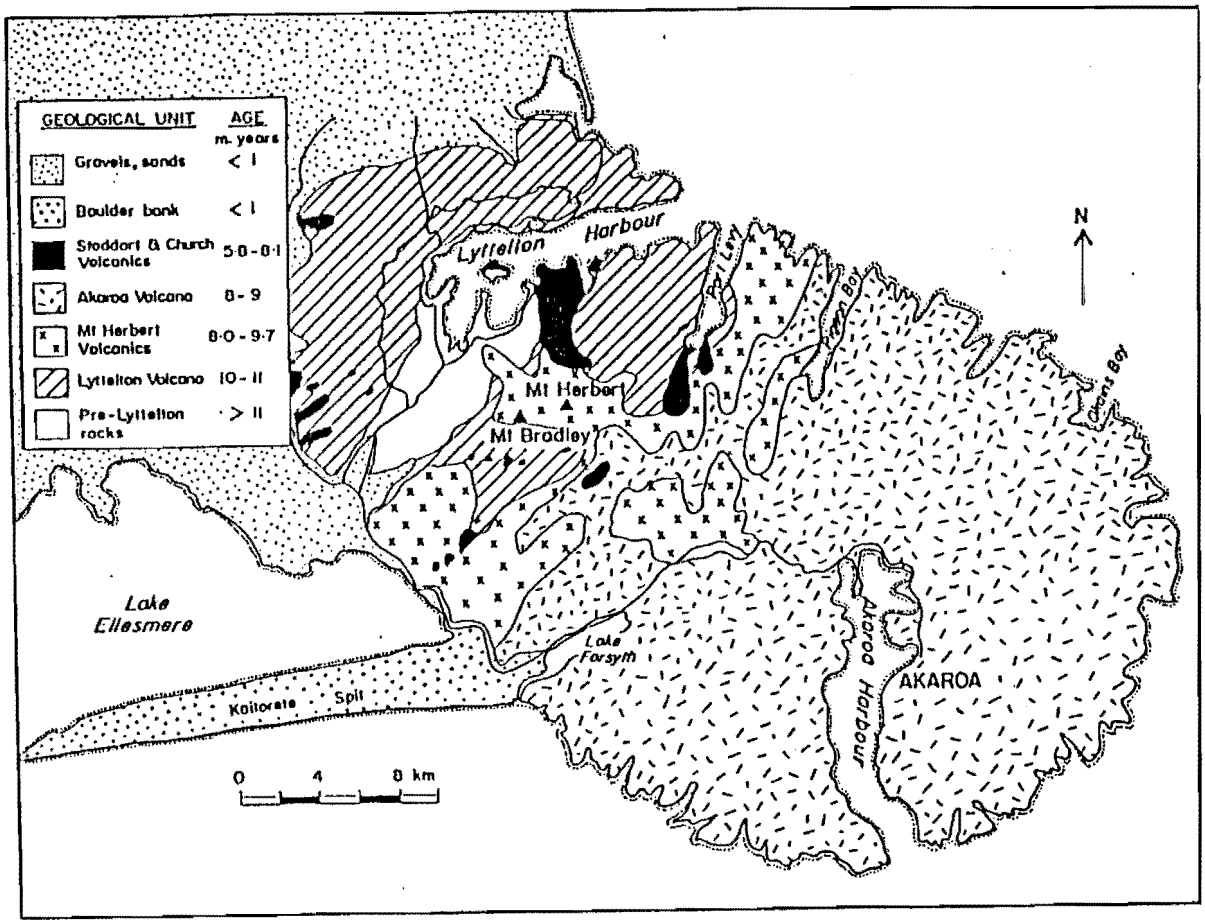


Fig. 1.7 Simplified geological map of Banks Peninsula.
(from Weaver et al, 1985).

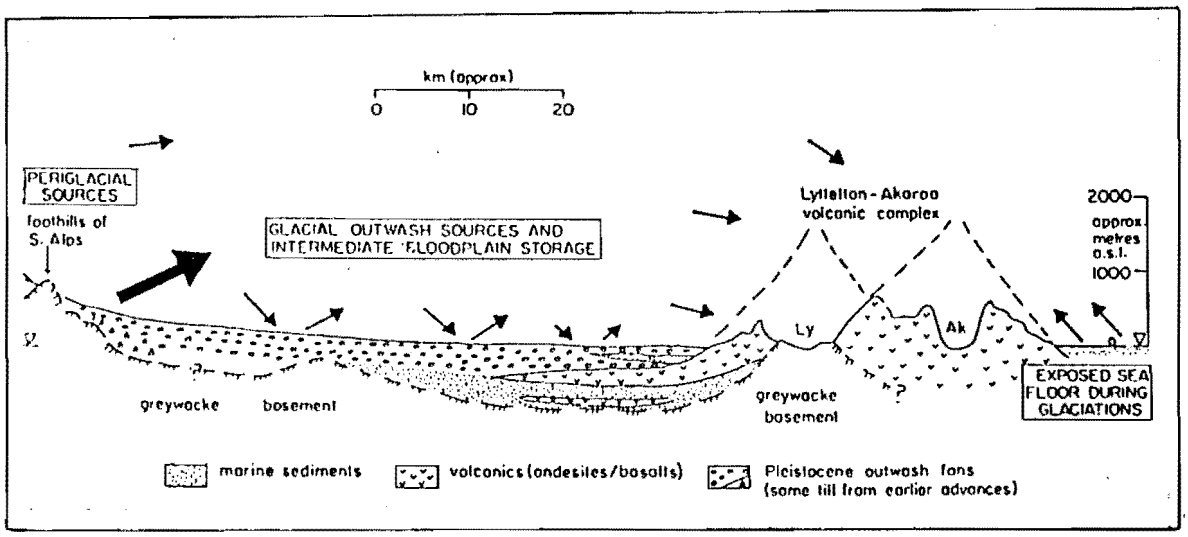


Fig. 1.8 Origin of Banks Peninsula loess deposits.
(from Bell & Trangmar, 1987).

redeposited down the volcanic slopes by freeze - thaw, and rainstorm induced mass movements during the Pleistocene (Griffiths 1974). Natural erosion processes have been further accelerated by human activity and residential development on the Port Hills.

Bell and Trangmar (1987) have suggested that five types of regolith can be recognized on the slopes of Banks Peninsula. These are;

1) In-situ loess
2) Loess-colluvium
3) Mixed deposits of loess and volcanic - derived colluvium
4) Volcanic-colluvium
5) Residual regolith.

The relationship between these regolith/ slope / erosion features is illustrated in Fig 1.9, while problems related to soil erosion and dispersion, as well as the mechanism of tunnel gully development, have been discussed in detail by Trangmar (1976) and Evans (1977).

Research by Griffiths (1973) has indicated the presence of two types of in-situ loess on Banks Peninsula, which he referred to as:

a) Birdlings Flats Loess, which is Coarse calcareous with textures of loamy fine sand and fine sandy loam and which is generally highly dispersive and slakes during saturation, and

b) Barry Bay Loess, which is Fine, non-calcareous and with a silt loam texture, and which possesses greater inter granular cohesion and lower dispersiveness relative to the Birdlings Flats Loess.

3) Loess-Colluvium Deposit

Loess-colluvium occurs mainly on the lower slopes of Banks Peninsula and includes all loessial material which has been transported down slope since initial deposition (Griffiths, 1973). It is principally composed of quartzofeldspathic silts and fine sands, but contains up to 10% volcanic clasts (Bell and Trangmar 1987). The distribution of loess deposits is illustrated in Fig 1.10.

1.4.2. Chemical stabilisation

On the Port Hills hydrated lime and phosphoric acid have been used to modify the erosive and dispersive characteristics of loessial soils (Evans, 1978 ; Evans and Bell 1981). The results of their research indicated that dispersive loessial soils are rendered erosion resistant with hydrated lime addition as low as 0.5% by weight of dry

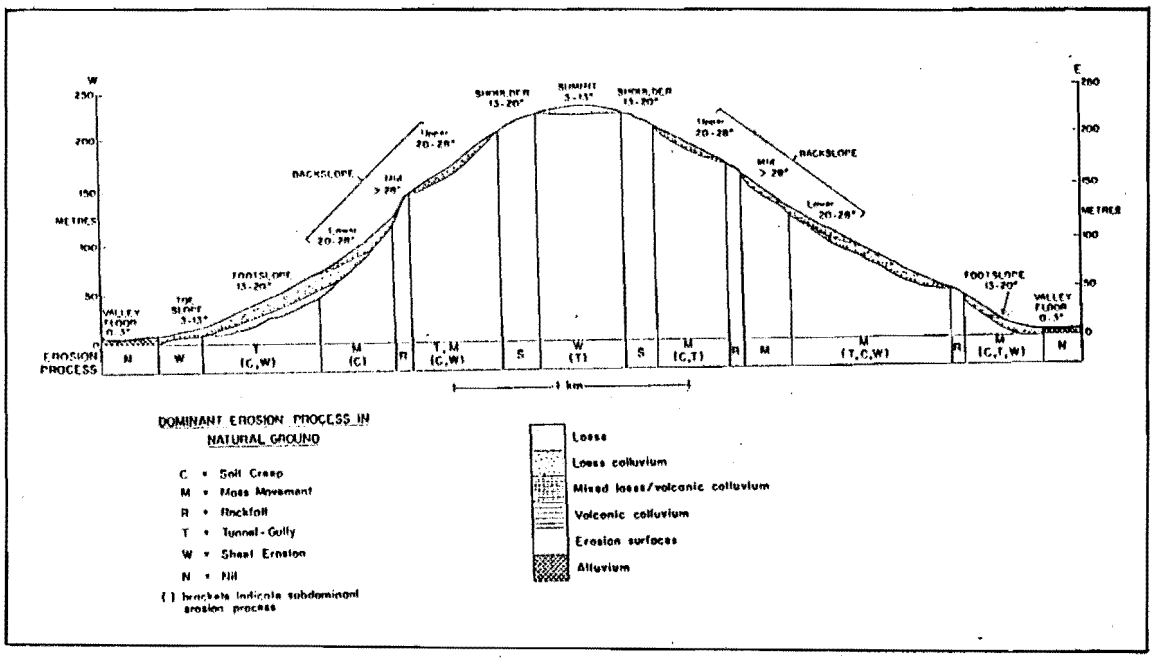


Fig. 1.9 Relationship between Slope/regolith type and erosion features on the Port Hills. (after Bell & Trangmar, 1987).

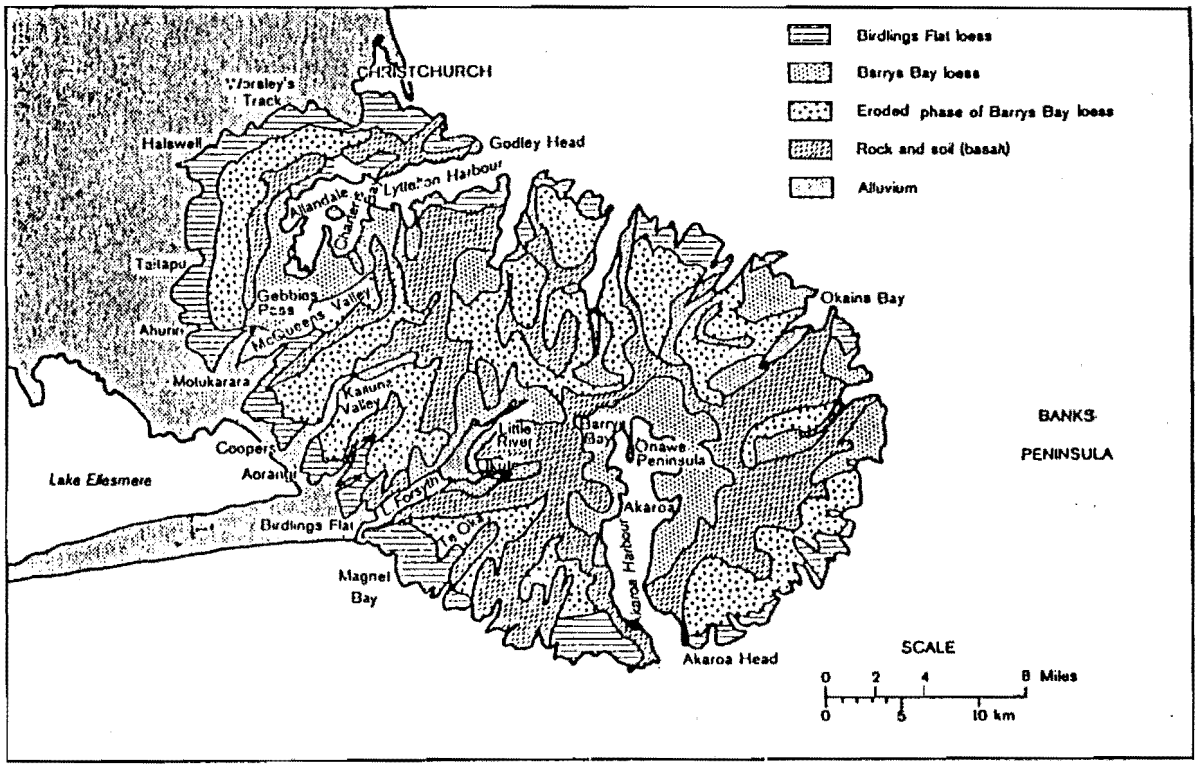


Fig. 1.10 Distribution of loess deposits on Banks Peninsula (after Griffiths, 1973).

soil. With 2% hydrated lime addition the swelling potential is minimised, while at approximately 5% unconfined compressive strength is maximised. In addition, Bell (1981, 1982 a and b) and McNeill (1982) have studied the field application of hydrated lime on Port Hills loess.

Glassey (1986) studied the effect of hydrated lime on index properties, dispersion and strength characteristics of Port Hills loess. His research indicated that 1) The addition of 1% hydrated lime to the loess soil produced a non-dispersive material; 2) with addition of 5% hydrated lime, the swelling potential is minimised, and 3) at about 7% hydrated lime addition, unconfined compressive strength is maximised.

Yetton (1986) has considered methods for identifying tunnel gully erosion in the field, and he also has applied lime-cement stabilisation techniques to infilling of cavities and/or their excavation and backfilling.

1.5. Site Description

1.5.1. Location

The Port Hills make up the north - western flanks of the eroded Lyttelton Volcano (Fig 1.1), separating the City of Christchurch from the Port of Lyttelton. The Whaka Terrace subdivision is located on the lower slopes of the Port Hills (Fig 1.2), and covers an area of about 2.8 ha. Relief on the subdivision varies between 100 and 150 m above sea level. A panoramic view from Whaka Terrace subdivision is shown in Fig 1.11. The subdivision plan includes 14 house sites and one reserve block, together with the development of road and sewage facilities (Fig 1.12-Map pocket).

1.5.2. Bedrock Geology

In this study rock and soil material were described according to the scheme of Bell and Pettinga (1985) and detailed description of terms is given in Appendix 1. The volcanic bedrock consists of a) moderately to highly weathered, weak greenish grey volcanic ash which forms relatively minor deposits and was found locally in auger holes 10 and 14 (lots 10 and 11 Fig 1.13 - map pocket); and b) slightly to moderately weathered, moderately strong reddish-brown closely jointed basaltic lava. Bedrock outcrops mainly consist of basaltic lava which

are generally discontinuous and irregular, and occur principally in the southern and south-eastern part of the subdivision (lots 6,7 and 12, which are also shown in Fig 1.12 - map pocket).

Seismic refraction profiles (Fig 1.13-map pocket) indicate that The depth to bedrock varies at different sites of the subdivision. Section A-A′ in the northern part of the subdivision illustrates the depth to bedrock is 1-2 m and indicates that the volcanic bedrock occurs as a series of stepped benches (1-2 m high) which are assumed to indicate different lava flows. Section C-C′ in the eastern part of the subdivision indicates a depth to bedrock of between 3-7 m. Auger holes drilled along the seismic profiles (Fig 1.13-map pocket) show the bedrock is overlain by loess-colluvium and mixed volcanic colluvium deposits.

1.5.3. Loess and Loess-Colluvium Deposits

Loess, loess-colluvium, mixed colluvium and volcanic colluvium (Bell and Trangmar 1987) cover the slopes at Whaka Terrace (Auger logs-Fig 1.13). Slopes have a westerly aspect, and slope angles vary between 15 and 35°. Loess deposits vary in thickness between 0.4 to 7 m.

Three soil units can be recognized within the loess deposits, which are classified according to Evans (1971) and are;

1) The S layer (or surface layer), which consists of 200 mm of top soil and 220 mm of friable grayish yellow sandy silt.

2) The C layer (or compact fragipan) comprising about 610-630 mm of stiff, dense and compact, yellowish brown silt which shows extensive shrinkage cracking.

3) The P layer (or parent material) which consists of dry, stiff, non plastic light olive/grey brown sandy silt (ML), and which is less dense than the C layer and tends to erode more readily.

The relationship between these units at Whaka Terrace is shown in Fig 1.14 (pit log).

1.5.4. Tunnel Gullies

Tunnel gullies provide the most serious erosion problem at the site. They are best developed in the central part of Whaka Terrace, where the thickness of loess-colluvium deposits is greatest (Fig 1.12 - map pocket). Two types of tunnel gullies have been recognized:

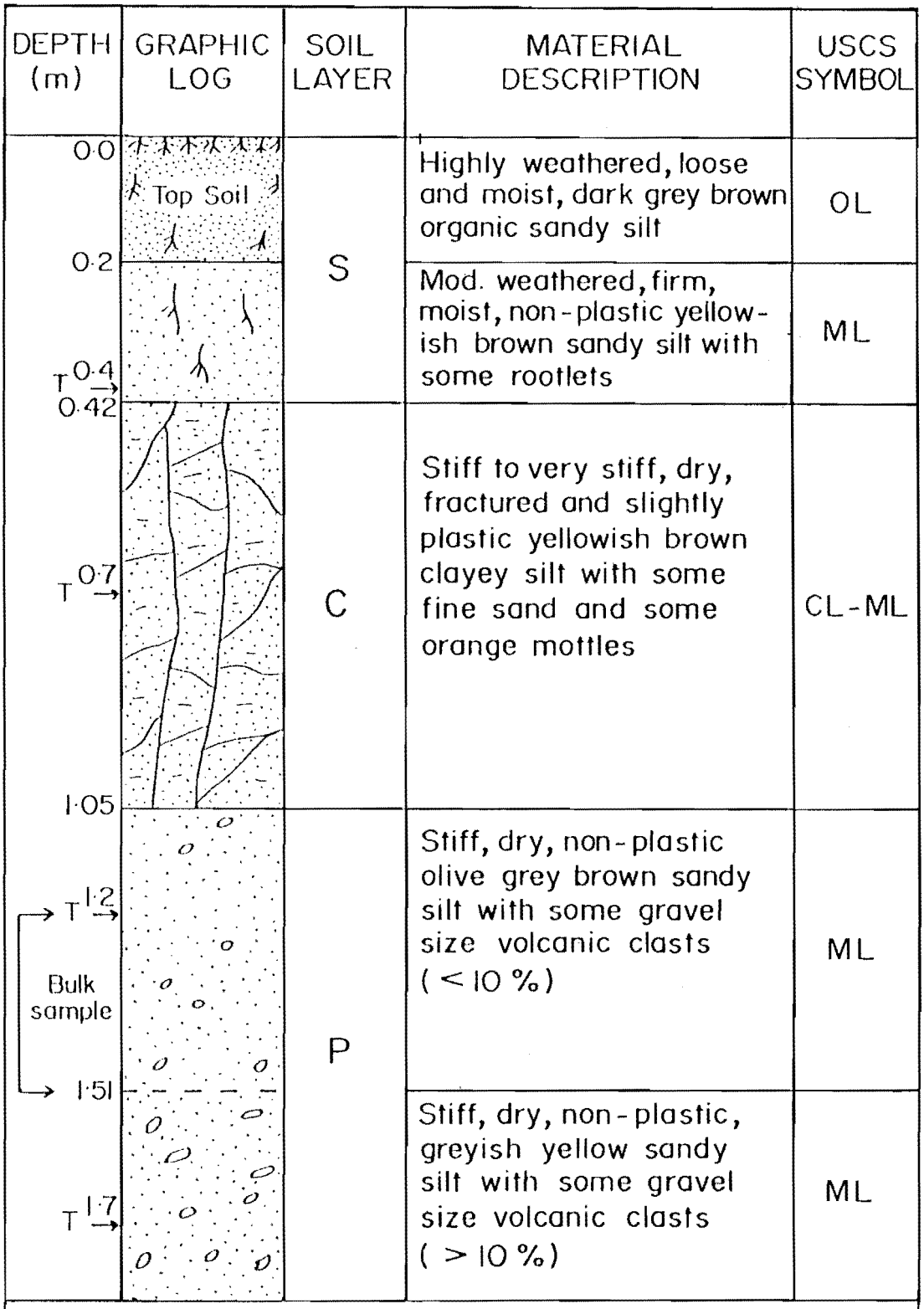


Figure 1.14 Summary pit log

a) Shallow cavities, which are restricted to locations above the fragipan which limits their vertical development. As a consequence they are generally less than 1m in depth, and usually less than 0.5m in diameter(Fig 1.15).

b) Deep cavity systems, which are located below the fragipan where their vertical development is not restricted.

1.5.5 Seepage Zones

Infiltration of groundwater from precipitation results in seepage zones at the boundary between bedrock and loess deposits. In addition, seepage can also be seen to occur from the exit of various tunnel gullies, which act as natural drainage paths (Fig 1.16). Seepage is most visible around Lot 15 above the access track (Fig 1.12 - map pocket) , and in the southern part of the subdivision where seepage and poor drainage produces a hummocky relief and swampy ground (Fig 1.12).

1.6. Investigation Methodology

1.6.1. Field Methods

Field work included engineering geological mapping of Whaka Terrace Subdivision at a scale of 1:500, and the construction of cross sections at a scale of 1:250. In addition, three seismic refraction traverses were carried out to determine the depth to bedrock. Seventeen auger holes were drilled along the seismic traverses and at other strategic points to verify the results from the seismic information, and to describe and log the soil profile. A backhoe (Fig 1.17) was employed to dig a sample pit of 2m depth and 2-2.5 m width at Grid reference 818374, (sheet 36, NZMS 260). Pit location is shown in Fig 1.12. map pocket. The pit was logged (Fig 1.14), and bulk and tube samples were taken for laboratory testing.

1.6.2. Laboratory Methods

Detailed laboratory characterisation was undertaken on tube and bulk samples from the loess-colluvium P - layer in the sample pit. Hydrated lime , gypsum, quicklime, Portland cement and a mixture of hydrated lime and gypsum (in a 1:1 ratio) were used as stabilising agents. Stabilisers were applied at ratios of 1, 2 and 4 % (as dry weight of soil) for different curing condition and periods during

Fig. 1.15a A typical shallow tunnel gully in loess soil at Whaka TC (Grid reference 816375 sheet 36, NZ. MS 260). Note fragipan layer at base of cavity.

Fig. 1.15b Various shallow tunnel gulies exposed during road construction in the eastern part of Whaka Terrace,(Grid reference 819373 - sheet 36,MS 260).

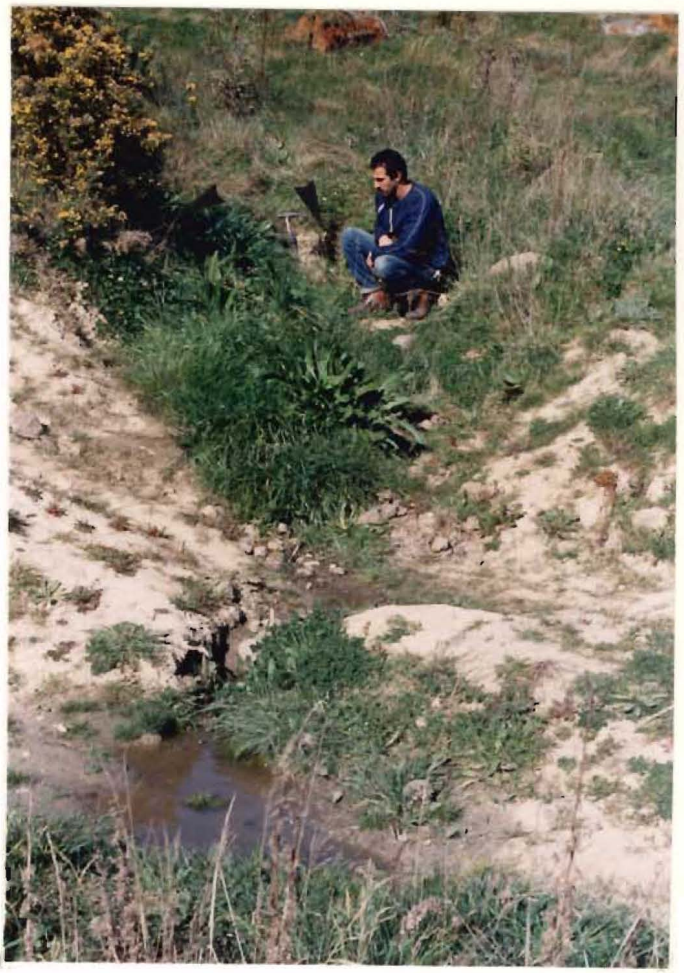


Fig.1.16 Seepage associated with exit of tunnel gullies in south of Whaka Terrace,(Grid reference 817374- sheet 36, NZ. 260).

Fig. 1.17 Collection of bulk sample using backhoe.

laboratory testing. Stabilisers available in 20 kg bag from commercial outlets were used, and they were stored in airtight plastic containers during testing.

The laboratory programme is detailed in chapter 2, and included:

I - Physical and Index characteristics tests.

a) In-situ moisture content and density
b) Grainsize Analysis
c) Plasticity
d) Standard Proctor Compaction
e) Permeability
f) Dispersion
g) Pinhole Erodibility
h) Uniaxial Swelling
i) Jar Slaking

II Strength Characterisation Tests

j) Unconfined Compressive Strength
k) Undrained Shear Strength

III Chemical and Mineralogical Tests

l) X-Ray Fluorescence (XRF)
m) Cation exchange and exchangeable bases
n) pH
o) Soluble salts
p) Organic content
q) X-Ray Diffraction (XRD)
r) Scanning Electron Microscopy (SEM)

1.7. Thesis Format

This thesis consists of five Chapters. The first Chapter is introductory and discusses the background and objectives of the study, as well as site geology and investigation methodology.

Chapter 2 deals with the physical and index properties of chemically stabilised loess soil relative to that of the natural soil. These properties are discussed in detail, particularly with respect to the erosion and dispersion characteristics as well as related parameters such as slaking and swelling.

Chapter 3 examines the strength characteristics of treated and untreated samples, in particular unconfined compressive strength and undrained shear strength.

In Chapter 4 the chemical composition and soluble salt concentration in pore water of natural soils, as well as changes in the cation exchange capacity, and soil $_{p}H$ of chemically stabilised samples were studied. In addition, the clay mineralogy of untreated samples and the mineralogy of stabilised samples, as related to crystallisation of the cementing agents have been studied by X-Ray diffraction, scanning electron microscopy and EDAX.

Finally, Chapter 5 presents the thesis summary and conclusions, and recommendations.

CHAPTER TWO: PHYSICAL AND INDEX PROPERTIES

2.1. Introduction

2.1.1. Sampling Methods

A 500 kg bulk sample was collected by backhoe from depths between 1.2 and 1.5 m below the ground surface in a sample pit (Fig 1.11, map pocket). The bulk sample may be described as; stiff, dry, non - plastic, olive grey brown sandy silt (ML), with some gravel size volcanic clasts (<10 %). The sample was stored in 3 large air tight plastic containers at room temperature in the Geology Department loading Bay. Tube samples were also collected from the sample pit from the different soil layers, and these were used for the determination of density and in-situ moisture content, dispersion, erodibility and swelling potential of the in-situ samples (Fig 2.1).

2.1.2. Laboratory Programme

The samples tested (both treated and untreated) were cured under three different conditions, as follows;

a) Moist curing for 14 days in the fog room at 20° C temperature and 99% relative humidity.

b) Air Drying for 7 days at room temperature following an initial period of moist curing for 7 days in the fog room (20° C and 99% relative humidity)

c) Wetting and Drying for 7 days (cycles of 4 hours wetting and 20 hours of drying) at room temperature following an initial period of moist curing for 7 days in the fog room.

The MC, AD, and WD abbreviations in the text that indicate moist cured, air dried, and wetting and drying conditions respectively.

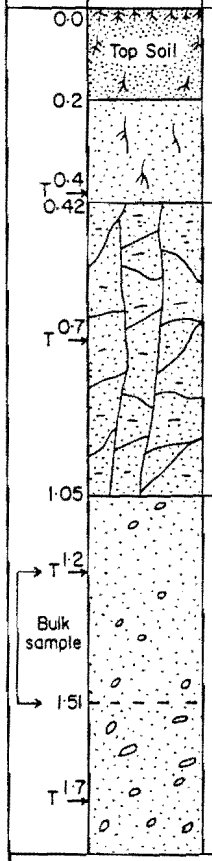
Figure 2.2. presents a schematic flow diagram of the tests performed on the natural soil and chemically stabilised samples.

The bulk sample was tested as:

1) Untreated and uncured (control) samples, which were tested to provide a basis for comparison with the chemically stabilised samples.

2) Treated and cured samples, which had been cured under the three different conditions discussed above, and treated by the application of different stabiliser agents.

Tests were carried out on uncompacted and recompacted samples, and the



DEPTH (m)	SOIL LAYER	MATERIAL DESCRIPTION	USCS SYMBOL	GEOTECHNICAL DATA: IN SITU MOISTURE CONTENT (w %)	BULK DENSITY (ρ tm^{-3})	DRY DENSITY (ρ_d tm^{-3})	MODIFIED EMERSON CRUMB CLASS (Sherared 1976)	PINHOLE ERODIBILITY CLASS	UNIAXIAL SWELLING (%)
0·0 – 0·2	S	Highly weathered, loose and moist, dark grey brown organic sandy silt	OL	10·5	—	—	1[1]	—	—
0·2 – 0·42	S	Mod. weathered, firm, moist, non-plastic yellowish brown sandy silt with some rootlets	ML	8·7	1·67	1·54	2-3[2]	E50[4]	15·5
0·42 – 1·05	C	Stiff to very stiff, dry, fractured and slightly plastic yellowish brown clayey silt with some fine sand and some orange mottles	CL-ML	7·4	1·78	1·66	1	NE[5]	6·7
1·05 – 1·51	P	Stiff, dry, non-plastic olive grey brown sandy silt with some gravel size volcanic clasts (< 10 %)	ML	7·1	1·64	1·54	3-4[3]	E50	18
1·51 –	P	Stiff, dry, non-plastic, greyish yellow sandy silt with some gravel size volcanic clasts (> 10 %)	ML	6·5	1·65	1·55	3-4	E50	21

T - Indicates location of tube samples

(1) - Non dispersive (2) - Slightly to moderately dispersive (3) - Moderately to highly dispersive (4) - Highly erodible (5) - Non erodible

SCALE 1:10

Figure 2.1: Summary pit log showing index properties for in-situ soil

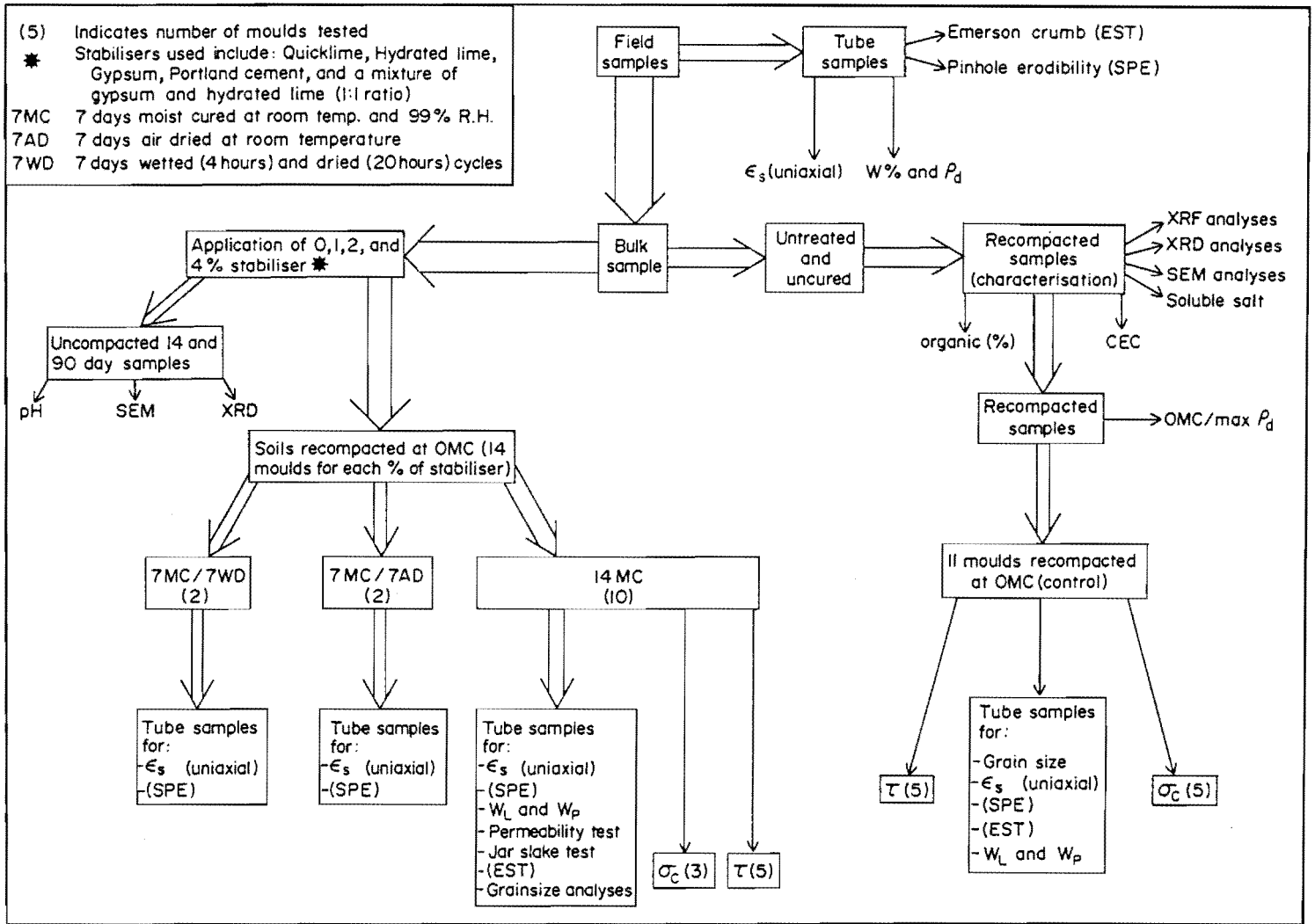


Figure 2.2 : Test programme summary

results are discussed in the following sections. Testing procedure for individual tests are summarized in appropriate Appendices 2-8.

2.2. Density/Moisture Content Relationships

2.2.1. In-Situ Samples

Tube samples were collected from depths of 40, 70, 120 and 170 cm (Fig 2.1.) to allow determination of the in-situ moisture content and dry density of loess-colluvium soil. Test procedure followed N.Z. Standard 4402 (1980), and is described in Appendix 2.

Figure 2.1. shows that moisture content is around 10%, with an average dry density of 1.55 tm^{-3}. In general in-situ moisture content is reduced with increasing depth, while dry density slightly increases. The most dense material belongs to the fragipan, with a dry density of 1.66 tm^{-3} . Data is summarized in Fig 2.1.

2.2.2. Recompacted samples

Previous research by Ladd and Lamb (1960), Hooper and Mitchell (1961), Herrin and Mitchell (1961), Alexander (1972) and Winterkorn (1975) has indicated that the effect of lime treatment is to increase the optimum moisture content, and to decrease the maximum compacted dry density of natural soil. This may be attributed to the flocculating effect of lime on the soil structure (Hooper and Mitchell, 1961). In general, the moisture content/dry density relationship depends on many factors. These are:

1) Type of lime; [Ladd and Lamb (1960) , and Alexander (1972)]

2) Clay content and clay mineralogy; [Croft (1964) , and Neubauer (1972)]

3) Elapsed time between mixing and compaction; [Mitchell and Hooper (1961) , and Mates and Davidson (1963)].

Research on Port Hills loess, by Evans and Bell(1981) , Yetton (1986) and Glassey (1986) indicated that there is a reduction in soil dry density and an increase in the optimum moisture content due to the application of hydrated lime. Furthermore, Evans and Bell (1981) studied the effect of phosphoric acid on Port Hills loess and their results indicated that there is a reduction in optimum moisture content and a corresponding increase in maximum compacted dry density.

In this study, standard compaction tests (proctor mould) on treated and untreated loess-colluvium soil were carried out, and test

results are illustrated in Fig (2.3 and 2.4). The test procedure is outlined in Appendix 2, and a summary of test data is given in Table 2.1 .

Figure 2.4 shows the untreated field sample has a maximum dry density of 1.86 tm^{-3} and an optimum moisture content of 13% . The effects of Portland cement, hydrated lime, quicklime, gypsum and a mixture of hydrated lime and gypsum (in a 1:1 ratio) on optimum moisture content and dry density are discussed in detail below.

2.2.3. Treated Samples

2.2.3.1. Lime-treated Samples

Figure 2.4 illustrates the effect of hydrated lime application on the optimum moisture content (OMC) and dry density of the soil tested in this study. The results show that at 1% by weight of hydrated lime addition the compacted dry density of the untreated sample decreases by 0.08 tm^{-3}, while the optimum moisture content increases by 1.7% from 13% to 14.7 % . At higher percentages of hydrated lime addition (2-4%) this trend continues but at a less pronounced rate: for example, at 4% hydrated lime addition the dry density has reduced by 0.13 tm^{-3} and the OMC has increased by 2.2% from 13% to 15.2% .

The results of this study agree with those from previous research, for example by Ladd and Lamb (1960); Mitchell and Hooper (1961); Alexander (1972); Winterkorn (1975); Evans and Bell (1981); and Glassey (1986). Test results for quicklime are similar (Figs 2.3 and 2.4).

2.2.3.2. Cement-treated Samples

Figure 2.4 and Table 2.1 suggest that the application of cement to Port Hills loess produces similar dry density / optimum moisture content relationships to those determined for hydrated lime and quicklime application. However, with application of 4% by weight of cement the optimum moisture content increases by a significant amount to 16.5% .

2.2.3.3. Gypsum-treated Samples

The test results (Fig 2.4) suggests that the application of gypsum has little effect on the compaction characteristics of loess soil. The data shows (Table 2.1) that at 4% by weight of gypsum

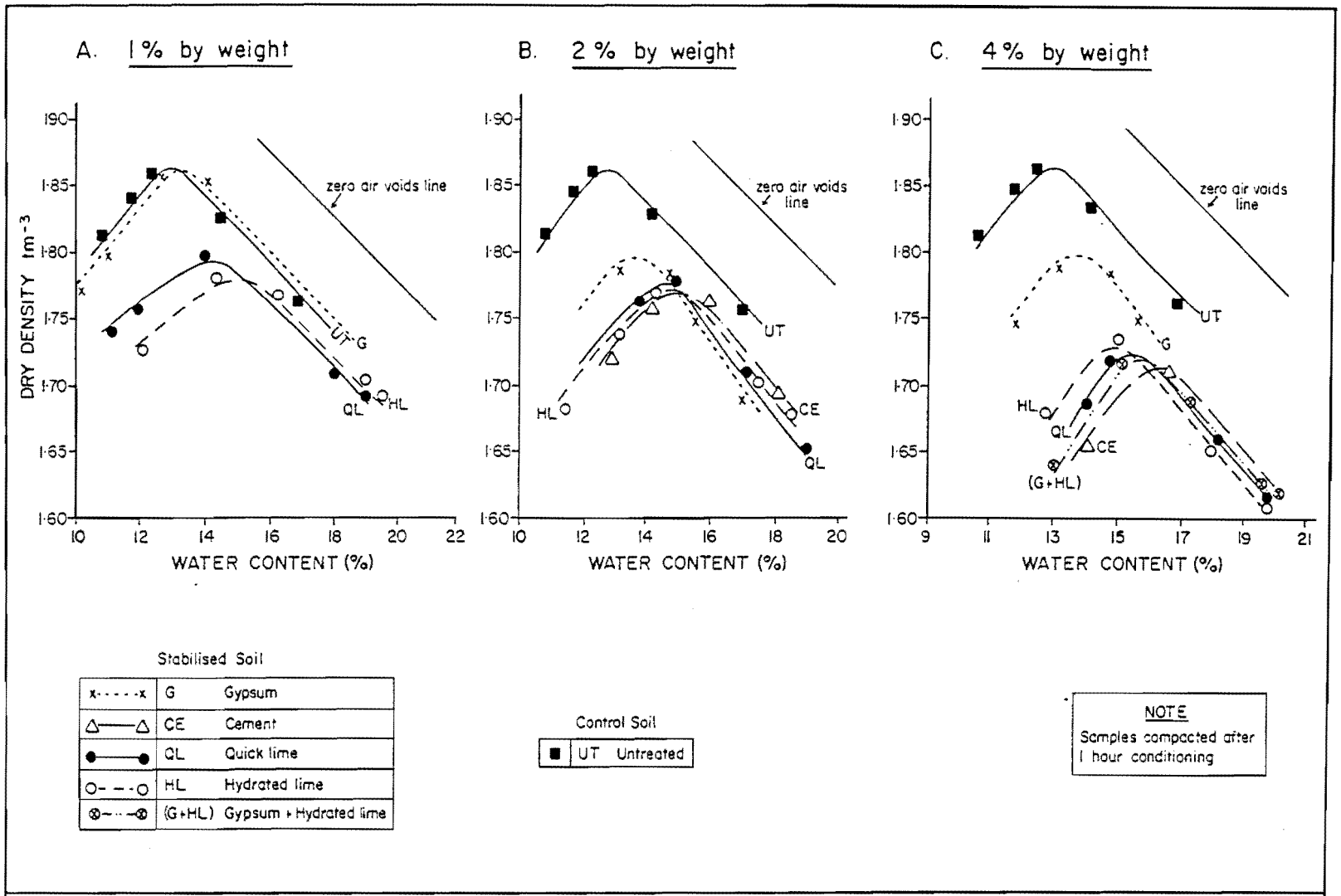


Figure 2.3: Effect of chemical stabilisers on optimum moisture content and dry density.

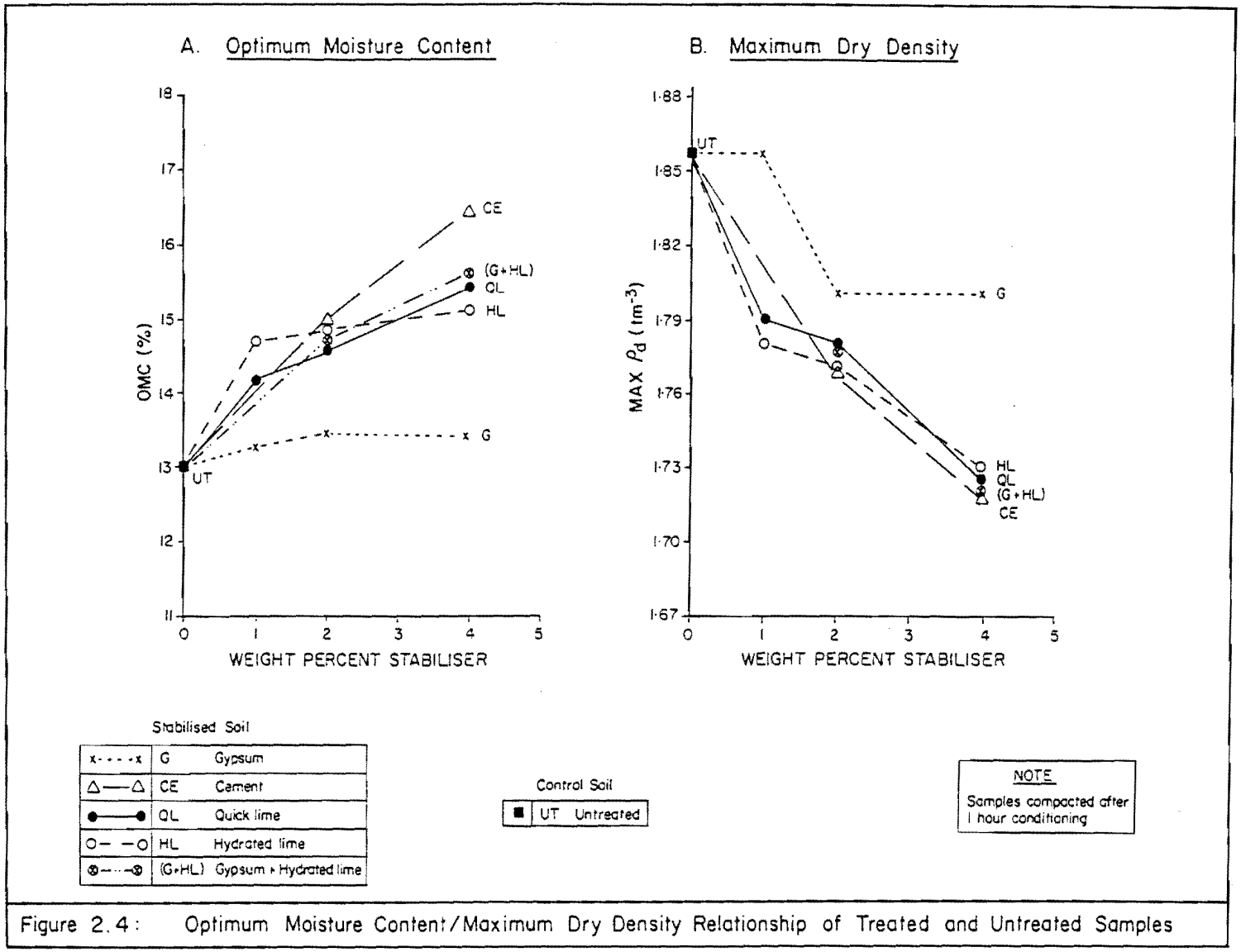


Figure 2.4: Optimum Moisture Content/Maximum Dry Density Relationship of Treated and Untreated Samples

Table 2.1 Effect of chemical stabilisers on dry density and OMC.

TYPE OF STABILISER	DRY DENSITY tm^{-3}	OPTIMUM MOISTURE CONTENT (OMC) %
UNTREATED		
SAMPLE (0%)	1.86	13.0
GYPSUM		
1%	1.86	13.3
2%	1.80	13.5
4%	1.80	13.5
QUICKLIME		
1%	1.79	14.2
2%	1.78	14.6
4%	1.72	15.5
HYDRATED LIME		
1%	1.78	14.7
2%	1.77	14.9
4%	1.73	15.2
PORTLAND CEMENT		
2%	1.77	15.0
4%	1.72	16.5
GYPSUM+Hydrated LIME		
2%	1.78	14.8
4%	1.72	15.7

application, the dry density is reduced by 0.06 tm^{-3}, while the OMC increases by 0.5% from 13.0 to 13.5% . This is related to flocculation of clay minerals, and an increase in void ratio of gypsum-treated samples.

Figure 2.4 illustrates that the application of 2-4% mixed stabiliser (hydrated lime and Gypsum in a 1:1 ratio) produces similar results to that of hydrated lime addition (2-4%).

2.3. Grainsize

2.3.1. Field Sample

Grainsize determination for untreated field samples and stabilised moist cured samples were made using dry sieve and hydrometer analysis. The test procedure for grainsize analysis is summarized in Appendix 3.

The results (Table 2.2) suggests that the untreated and uncured loess-colluvium sample from Whaka Terrace consists of a slightly sandy clayey silt containing 10 % sand, 14% clay, and 76% silt respectively. The untreated moist cured sample consist of 10% sand, 12% clay and 78% silt.

2.3.2 Stabilised Samples

2.3.2.1. Hydrated lime-treated Samples

Brand and Schonenberg (1959) ; Lund and Ramsey (1960) ; Herrin and Mitchell (1961) ; Brandl (1981) ; and Glassey (1986) all have indicated that the addition of hydrated lime to a moist soil produces a decrease in silt and clay content, and an increase in sand percentage. Analysis of Fig 2.5 indicates that:

1) with addition of 1% by weight of hydrated lime, a marked reduction in clay content by 6% is noticeable, and this is accompanied by a corresponding increase in the proportion of sand whilst the silt percentage remains almost unaffected;

2) at 2% by weight of stabiliser addition, a marked reduction in silt content is observed in addition to the decrease in clay content, with a correspondingly greater increase in the sand percentage;

3) further increases in the percentage of stabiliser used (for example 4%) show that the coarsening trend of grainsize distribution

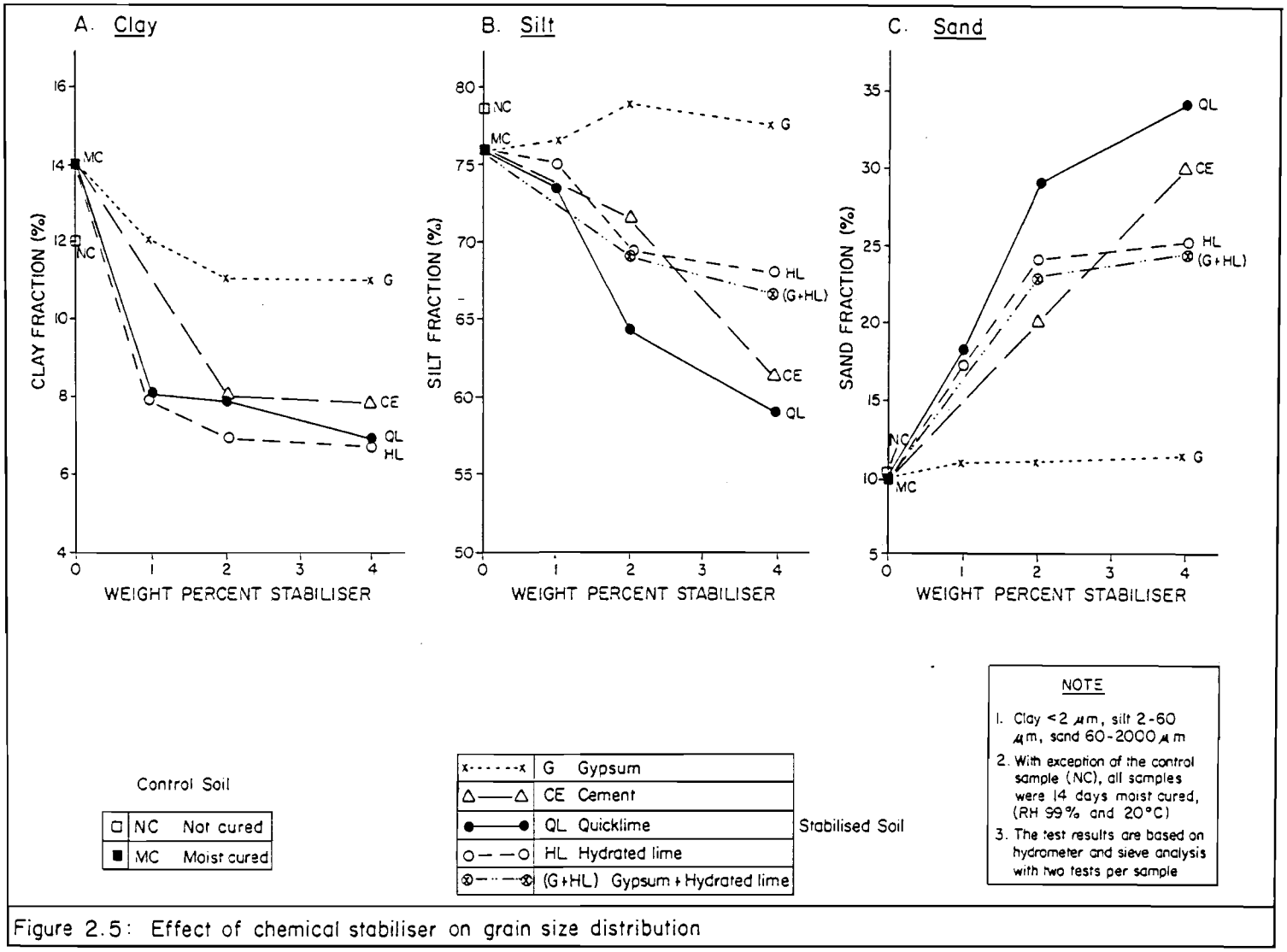


Figure 2.5: Effect of chemical stabiliser on grain size distribution

Table 2.2 Effect of chemical stabilisers on grainsize distribution.

TYPE OF STABILISER	SAND% 2000-60 μm	SILT% 60-2 μm	CLAY% < 2 μm
FIELD SAMPLE			
NOT CURED (0%)	10	76	14
RECOMPACTED			
MOIST CURED (0%)	10	78	12
GYPSUM			
1%	11	77	12
2%	11	78	11
4%	12	77	11
QUICKLIME			
1%	18	74	8.0
2%	29	63	8.0
4%	34	59	7.0
HYDRATED LIME			
1%	17	75	8.0
2%	24	69	7.0
4%	25	68	7.0
PORTLAND CEMENT			
2%	20	72	8.0
4%	30	62	8.0
GYPSUM+HYDRATED LIME			
2%	23	69	8.0
4%	25	67	8.0

continues, but at decreasing increments.

The results suggest that at 1% addition by weight of hydrated lime the stabiliser is used up in its reaction with the clay fraction, while at 2% addition the stabiliser is sufficient to react with both the clay and silt size particles, as suggested by the reduction in the silt content. Fig 2.5 shows that 2% hydrated lime is the optimum loess/stabiliser mixture for increasing the sand size fraction, while higher percentages of stabiliser have decreasing effectiveness.

The results from this study indicate an increase in sand size particles with the application of hydrated lime at 1, 2, and 4% . These results agree with the overall trend described by Glassey (1986), implying an increase in sand size with hydrated lime addition. However, Glassey suggested a decrease in sand size particles from 14% for natural soil to 10% upon application of 1% hydrated lime. This result is not supported by the finding of the present study, or by research from Lund and Ramsey (1959) which are shown in Fig 2.6 .

In summary, laboratory study suggests that the application of hydrated lime to Loess-colluvium soils from Whaka Terrace has the effect of changing the grainsize distribution, and it may be reclassified from a slightly sandy clayey silt to a sandy silt (24% sand, 69% silt and 7% clay with 2% hydrated lime addition).

2.3.2.2. Quicklime-treated Samples

The effect of quicklime on the grainsize distribution of the loess-colluvium samples is similar to that for hydrated lime, but its effect is much more pronounced (Table 2.2). Figure 2.5 (c) illustrates an increase in the sand size fraction from 10% for field sample to 18 and 29% upon application of 1 and 2% quicklime respectively. The greatest percentage increase in sand size fraction is obtained with the addition of 2% quicklime.

2.3.2.3. Portland Cement-treated Sample

The addition of Portland Cement to loess-colluvium samples after 14 days moist curing has a similar effect to that of both hydrated lime and quicklime. Test results suggest, however, that application of 4% cement is more effective than 2% cement in increasing the sand size fraction of the samples (Figure 2.5c). Also it can be seen that although the application of 2% Portland cement has a significant effect on grainsize distribution, its effect is less

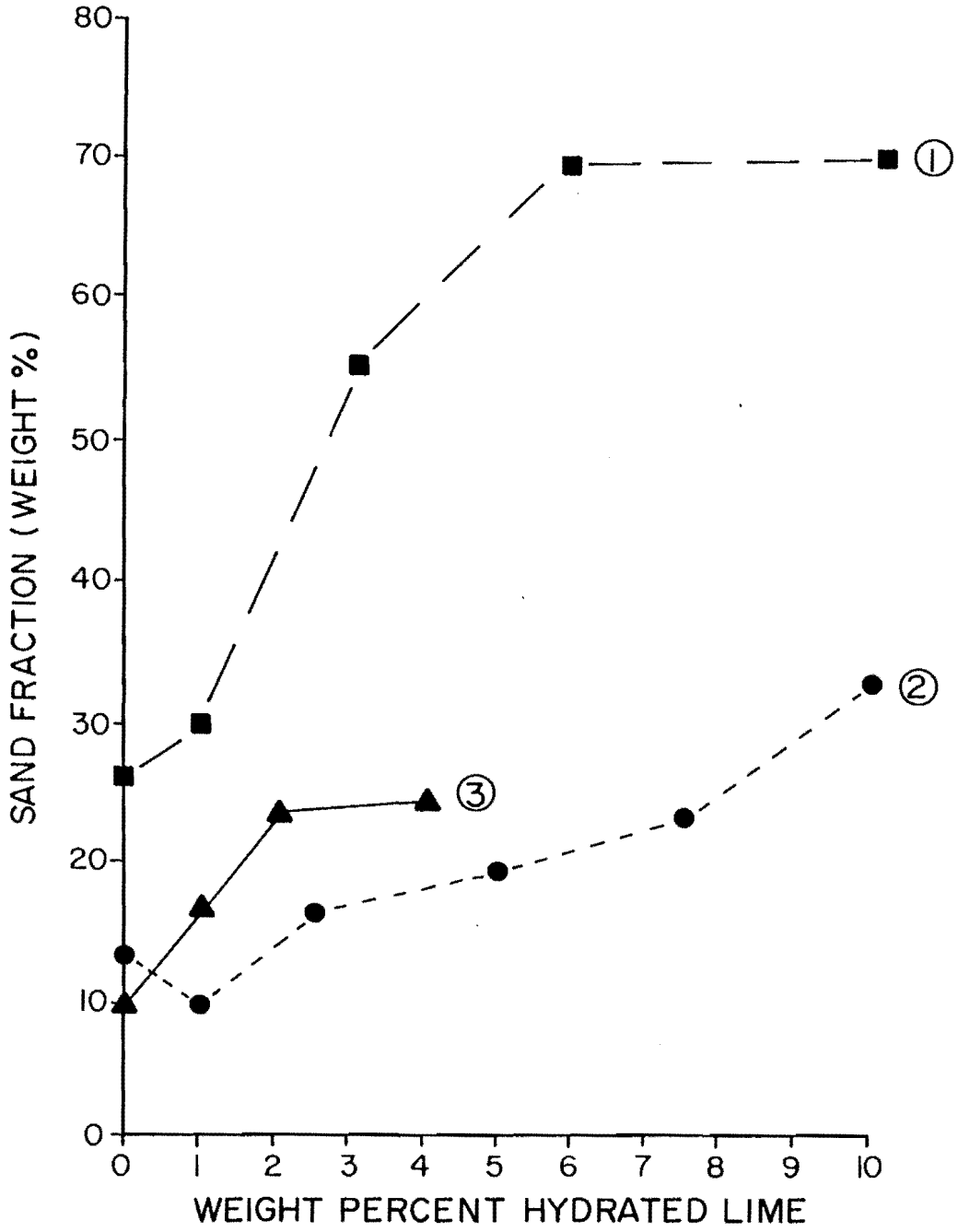


Figure 2.6: The effect of the application of hydrated lime on the sand size fraction of different soils

① - Glacial clay (sand 31%, silt 33%, clay 36%) south of Nebrasca, Lund & Ramsay (1959)

② - Loess colluvium (sand 14%, silt 65%, clay 21%) Port Hills, Glassey (1986)

③ - Loess colluvium (sand 10%, silt 76%, clay 14%) Port Hills, This Study

pronounced than that of 2% hydrated lime and quicklime.

2.3.2.4. Gypsum-treated samples

Figure 2.5 shows that there is no appreciable change in grainsize distribution of the loess-colluvium samples resulting from the application of gypsum. The small reduction in clay content (2-3%) and the small increment on the percentage of silt (1 -2%) is due to the flocculation of clay particles. Therefore, while gypsum acts as a flocculant, it does not appear to produce a cementing agent which will bond the silt particles into larger aggregates.

2.3.2.5. Mixed hydrated lime and gypsum-treated samples

The test results suggest that the application of a mixture of hydrated lime and gypsum (1:1 ratio) is comparable with the effect of pure hydrated lime addition. For example, with application of 2% mixed stabiliser, and hydrated lime a reduction in silt fraction (from 78% for untreated sample to 69% for stabilised samples) as well as a reduction in clay fraction (from 12% for untreated sample to 7-8% for stabilised samples) is observed. this is accompanied by a corresponding increase in the sand fraction (from 10% for untreated sample to 23-24% for stabilsed samples).

2.3.2.6. Summary

In summary, the following effects of different stabiliser agents on the grainsize distribution of Whaka Terrace loess-colluvium soil have been observed:

1) of the four stabilisers used, three (hydrated lime, quicklime and cement) have the effect of reducing the clay and silt fraction of the soil by flocculation and agglomeration, resulting in an increase in the sand size fraction of the soil. The fourth stabilising agent (gypsum) was found to be ineffective in increasing the sand size fraction.

2) Quicklime was found to be the most effective stabiliser with regard to increasing the sand size fraction.

3) For quicklime and hydrated lime it was found that the application of 2% by weight of stabiliser produces the largest percentage increase in the sand size fraction.

4) For cement it was found that the application of 4% by weight of stabiliser produces a greater percentage increase in sand

size fraction than the 2% application, and this contrasts with the results for lime stabilised samples.

2.4. Plasticity

2.4.1. Test Methods

A review of the literature suggests that the effect of lime on the plasticity of natural soil is variable and dependent on many factors. In summary these are:

1) The type of clay mineral and the amount of clay present in the soil (Lund and Ramsay, 1959; and Fosberg, 1969).

2) Type and amount of lime applied (Stocker, 1975).

3) Composition of the pore water and the exchangeable cations originally present in the soil (Grim, 1962).

In this study Atterberg limit tests were carried out to determine the effects of chemical stabilisers on the plasticity characteristics of loess-colluvium soil from Whaka Terrace. Test procedures are outlined in Appendix 2 and laboratory results are shown in Fig 2.7 and Table 2.3.

2.4.2. Treated and Untreated samples

Figure 2.7 shows that the untreated field sample has liquid limit = 24, plastic limit = 17, and plastic index = 7, which indicates a clayey silt of low to very low plasticity. The activity (plasticity index/percentage of clay fraction) of the soil is 0.70 (Fig 2.8). These activity and plasticity data correspond to the activity of illitic types of soil (Skempton, 1953; Seed et al, 1964).

2.4.2.1. Lime-treated Samples

Figure 2.7 shows that the addition of 1-2% hydrated lime by weight of dry soil produces an increase in the plasticity by 2 - 3, and that this results from a marked increase in the liquid limit at 2% addition. At 4% hydrated lime addition the plasticity decreases, due to a marked increase in the Plastic limit. In general the data indicates that for applications of 2% or less the increment of change in the liquid limit exceeds that of the plastic limit, while at treatments in excess of 2% the plastic limit continues to increase while the liquid limit remains almost unchanged. The result of this study does not agree with Glassey (1986) who suggested that the plastic Index of 1, 2.5, and

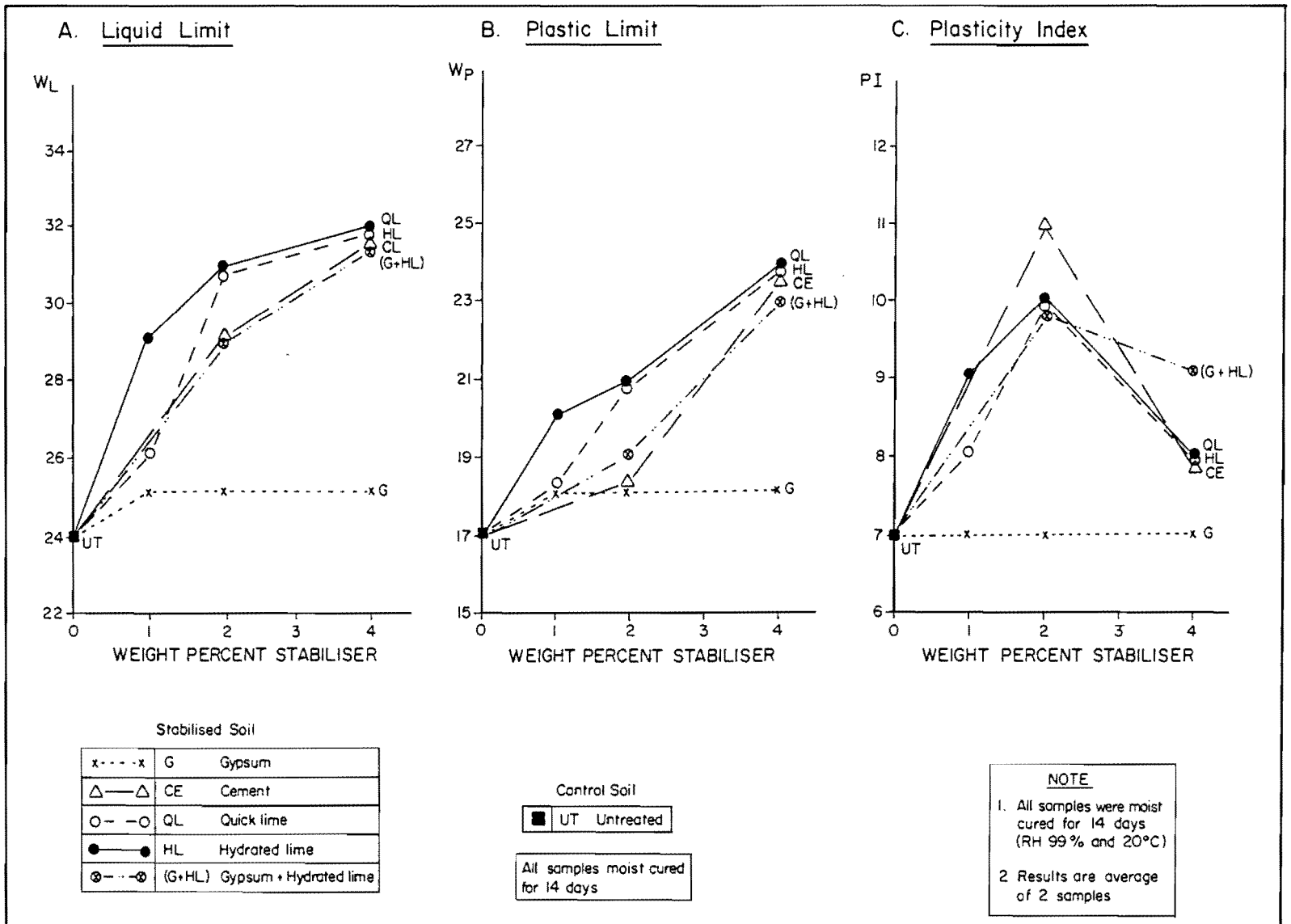


Figure 2.7 : Effect of Chemical Stabilisers on Plasticity Characteristics

5% hydrated lime-treated samples were 13.1, 13.0, and 13.0 respectively.

Analysis of Fig 2.7 indicates that with up to 2% hydrated lime application the activity of loess soils increases from 0.7 to 1.42, corresponding to the reduction in clay content and increase in plastic index. In excess of 2% stabiliser addition, the activity of the loess-colluvium is reduced, and this trend is in agreement with previous research by Clare and Cruchely (1957), and Brandl (1981).

2.4.2.2. Quicklime-treated Samples

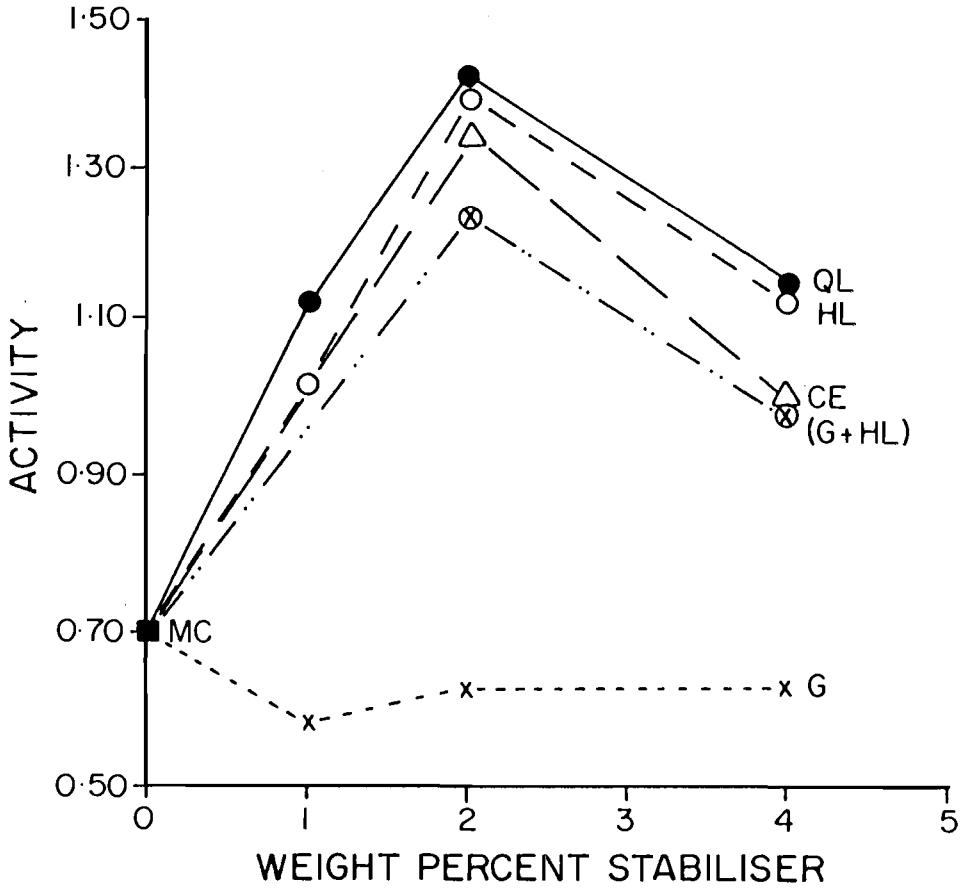
The effect of the application of quicklime on plasticity and activity of loess-colluvium soil is similar to the effect of hydrated lime (Fig 2.7and 2.8). The test results (Table 2.3) suggest that with the application of 1 and 2% quicklime the plasticity index increases from 7 for untreated samples to 10 for stabilised samples. The increase in the plasticity index is result of an increase in the liquid limit (from 24 for untreated samples to 31 for stabilised samples) as well as an increase in the plastic limit (from 17 for untreated sample to 21 for stabilised sample). At 4% quicklime addition the plasticity index of stabilised samples decreases due to a high increase in the plastic limit (from 21 for 2% stabilised samples to 24 for 4% stabilised samples).

2.4.2.3. Cement-treated Samples

Test result(Table 2.3) indicate that cement application produces a similar response to that of hydrated lime and quick lime. At 2% cement application the plastic index increases significantly, mainly as a result of an increase in the liquid limit, while the plastic limit remains almost unchanged. It therefore differs from the application of lime, and reinforces the results of grainsize analysis whereby major changes become apparent at 4% application of cement rather than 2% .

2.4.2.4. Gypsum-treated samples

Figure 2.7 shows that the application of gypsum has no effect on the plasticity of loess-colluvium soils. Furthermore, in the mixture of gypsum and hydrated lime (1:1 ratio) the results are almost the same as for hydrated lime.



Stabilised Soil

●——●	QL	Quicklime
○— —○	HL	Hydrated lime
△——△	CE	Cement
⊗—··—⊗	(G+HL)	Gypsum + Hydrated lime
x-----x	G	Gypsum

Control Soil

■	MC Moist cured

All samples moist cured for 14 days

Figure 2.8: Activity of treated and untreated loess-colluvium sample from Whaka Terrace, Port Hills.

Table 2.3 Effect of chemical stabilisers on plasticity and activity.

TYPE OF STABILISER	LIQUID LIMIT(WL)	PLASTIC LIMIT(WP)	PLASTIC INDEX(PI)	ACTIVITY (Ac)
UNTREATED SAMPLE				
0%	24	17	7	0.7
GYPSUM				
1%	25	18	7	0.58
2%	25	18	7	0.63
4%	25	18	7	0.63
QUICKLIME				
1%	29	20	9	1.12
2%	31	21	10	1.42
4%	32	24	8	1.14
HYDRATED LIME				
1%	26	18	8	1.0
2%	31	21	10	1.42
4%	32	24	8	1.14
PORTLAND CEMENT				
2%	29	18	11	1.37
4%	32	24	8	1.0
GYPSUM+HYDRATED LIME				
2%	29	19	10	1.25
4%	32	23	9	1.0

2.5. Permeability

2.5.1. Test Methods

In this study permeability characteristics of treated and untreated loess-colluvium from Whaka Terrace were investigated using falling head permeability tests (Fig 2.9). The field sample and stabilised samples were compacted in a Proctor mould (105 mm diameter) in a single layer, and were then moist cured for 14 days at 99% relative humidity and 20° C). The test method is outlined in appendix 4, and data are summarised in Table 2.4.

2.5.2. Treated and Untreated samples

Figure 2.10 shows that the untreated recompacted field sample has a coefficient of permeability of 2 x 10^{-8} ms^{-1}), a bulk density of 2.06 tm^{-3} and a dry density of 1.84 tm^{-3}. The laboratory results (Table 2.4) indicate that the permeability of Whaka Terrace loess-colluvium increases as a result of the application of chemical stabilisers, and in summary it can be seen that:

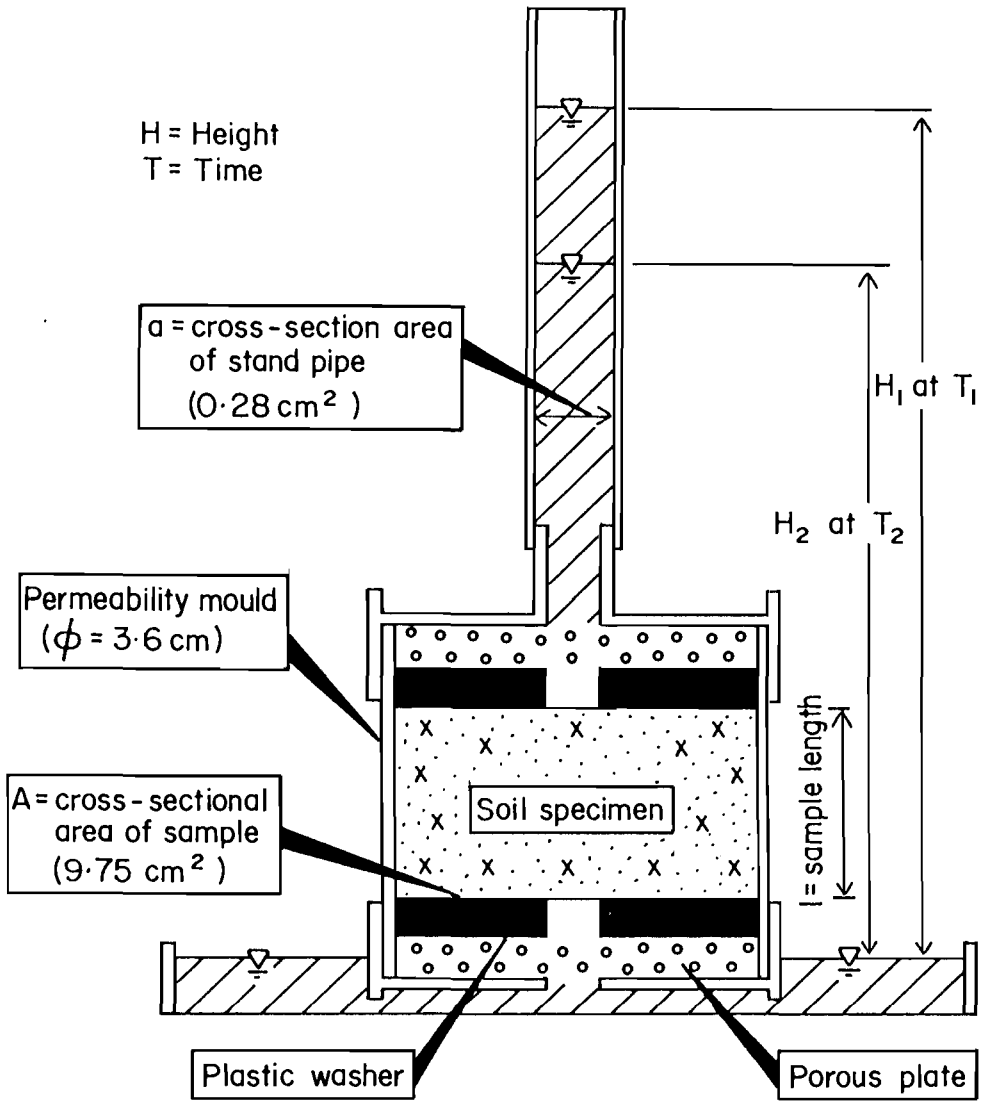
1) The application of 1% by weight of hydrated lime and quicklime produces an increase in the coefficient of permeability of about 100 times (2 x 10^{-8} m/s to 2.6 x 10^{-6} m/s). This trend continues with increasing lime content, but at decreasing effect-iveness.

2) The application of Portland cement has a similar effect on the permeability of loess soil to that of hydrated lime and quicklime (Table 2.4. and Fig 2.10).

3) The application of gypsum produces an increase in the coefficient of permeability by almost ten times relative to the untreated samples (Fig 2.10).

4) There is an inverse relationship between compacted density and permeability of hydrated lime, quicklime and cement-treated samples. This is due to flocculation of clay and agglomeration of silt size fraction of the stabilised soil, results in an increase of sand fraction (section 2.3.2.) therefore, the pore volume increases and the bulk density of saturated soil decreases, thereby increasing soil permeability (Fig 2.10b).

5) The trend obtained in this study (an increase in soil permeability in soil/lime mixtures after 14 days moist-curing) is supported by the result of Evans and Bell (1981), who also obtained an increase of permeability of the order of 10^2 from the application of 1%



$$K = \frac{al}{A} \times \frac{\log_e (H_1 / H_2)}{(T_2 - T_1)}$$

K = coefficient of permeability

Figure 2.9: Sectional View of Falling Head Permeability Apparatus (from Scott, 1980)

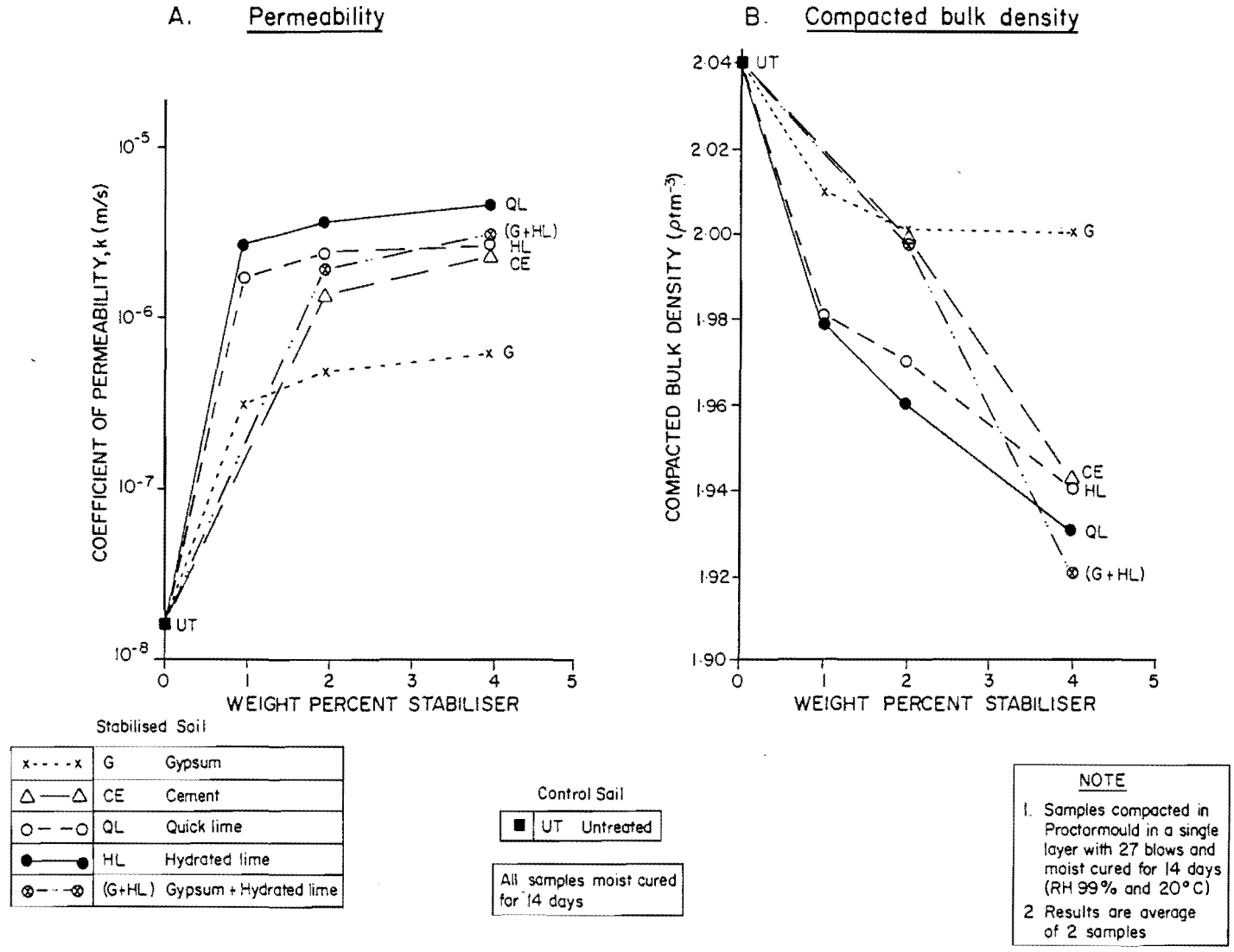


Figure 2.10: Permeability and compacted density.

Table 2.4 Permeability of treated and untreated samples.

TYPE OF STABILISER	COEFFICIENT OF PERMEABILITY(K=m/s)	BULK DENSITY tM^{-3}
UNTREATED SAMPLE		
0%	2.0×10^{-8}	2.06
GYPSUM		
1%	5.1×10^{-7}	2.03
2%	7.0×10^{-7}	2.0
4%	7.8×10^{-7}	2.0
QUICKLIME		
1%	4.5×10^{-6}	1.98
2%	5.6×10^{-6}	1.96
4%	6.7×10^{-6}	1.93
HYDRATED LIME		
1%	2.6×10^{-6}	1.98
2%	3.6×10^{-6}	1.97
4%	4.5×10^{-6}	1.94
PORTLAND CEMENT		
2%	1.5×10^{-6}	2.0
4%	4.3×10^{-6}	1.94
GYPSUM+HYDRATED LIME		
2%	2.8×10^{-6}	2.0
4%	4.9×10^{-6}	1.92

hydrated lime to Port Hills Loess.

6) The principal aims of chemical stabilisation in Port Hills loess are to reduce soil erodibility and dispersiveness, as well as to improve soil strength and durability. Changes in soil permeability are an additional side affect derived from chemical stabilisation.

2.6. Dispersion/Erosion

2.6.1. Background

Research by Hughes, 1970; Miller, 1971; Evans, 1977; and Saul, 1979 has indicated that dispersion is an important factor controlling soil erodibility. The access of water to dispersive soil layers enables clay minerals to be placed in suspension and to be removed by water movement. Furthermore, the removal of clay particles reduces the cohesive component of the soil, destabilising the soil skeleton and resulting in the subsequent removal of silt and sand particles by slaking and other physical erosion processes (Evans, 1977; and Bell, (1981a), leading to the initiation of tunnel gully development as well as rill and sheet erosion.

Dispersion is a physico-chemical process involving the deflocculation of clay particles in water (Holmgren and Flanagan, 1977), while soil erodibility refers to the processes involving the separation and removal of soil particles by the action of flowing or infiltrating water. Factors contributing to soil dispersion/erosion as suggested by Bell (1982) and this study are:

a) The concentration of sodium cations and soluble salts in the soil.

b) Chemistry of pore water and the infiltrating water.

c) Initial moisture content of the soil by providing an energy level that must be exceeded before particle separation occurs.

d) Arrangement of clay particles in the soil.

e) Amount and type of clay minerals (influencing the cohesive potential of the soil).

f) Type and amount of cementing agents, (such as FeO, SiO_2 and $CaCO_3$) present to bind the soil skeleton and to prevent erosion.

g) Magnitude of the shear stress generated by flowing water at the soil/water interface, and the volume of water available to remove detached soil particles.

The pinhole test was initially developed by Sherard et al (1976a) with the aim of determining the dispersion potential of recompacted fine-grained soils. The test consists of drilling a 1 mm diameter hole through the center of a cylindrical specimen. Water is then passed through the specimen under various amounts of head. Samples are categorized into six classes namely D1 and D2 for dispersive soils, and ND1 to ND4 for non -dispersive soils.

Evans (1977) adapted the pinhole test to determine the erodibility of in-situ loess samples from Banks Peninsula. However research by Schafer and Trangmar (1981), Yetton (1986) and Glassey (1986), suggest that there is a lack of correlation between results from the pinhole test and other tests measuring soil dispersion (such as the Emerson Crumb Test and pore water analyses). Yetton (1986) suggested that the Emerson crumb test is a more reliable test for soil dispersion, and it has therefore become widely used as the standard test for determination of dispersion of Port Hills loess.

Yetton (1986) and Glassey (1986) modified Sherard's pinhole classification for dispersive soils with the aim of emphasizing the measurement of soil erodibility, rather than colloidal dispersion. The Yetton and Glassey classification plots water discharge (mls^{-1}) versus the elapsed time (minutes) for each head. From this graph, the head which produces a continuous increase in the flow rate over a three minute period or more provides a basis for classification of soil erodibility (refer to Appendix 6). In this study the pinhole test have been used to determine the erodibility of treated and untreated samples and results are classified using the scheme of Yetton and Glassey.

Kawamura et al (1975) studied the erodibility of lime and cement stabilised soil under the influence of artificial rainfall. His results indicates that small percentage of hydrated lime or portland cement will prevent particle detachment under the impact of raindrops. Mechon et al (1977) studied the effect of hydrated lime on soil erodibility and concluded that the increase in erosion resistance of the soil is due to the crystallisation of insoluble hydrated calcium silicate and aluminate around the soil particles. He observed that the new minerals, cement the soil particles thereby improving inter-granular bonding. Research by Evans and Bell (1981) and Glassey (1986) on erodible loess-colluvium samples from the Port Hills indicate that all samples are rendered non-erodible (ND1 or NE) with the application of hydrated lime at concentrations as low as 1% by weight

of dry soil.

2.6.2. Test Methods and Results

The dispersion of the loess-colluvium soil was tested using the Emerson Crumb Test (1967) and the Modified Crumb Test (Sherard, et al 1976). The procedure for the Emerson Crumb Test is described in Appendix 5, along with the modified procedure of Sherard et al 1976.

The standard pinhole test were carried out on Whaka Terrace loess-colluvium soil to determine the erodibility of; (i) untreated in-situ samples, (ii) untreated recompacted samples and (iii) chemically stabilised samples. Stabilised sample were cured under three different condition prior to testing namely, moist curing, air drying, and wetting and drying (section 2.3.). Test results are summarised in Table 2.6; Fig 2.12 and Figs A6.5 to A6.17. The test procedure is outlined in Appendix 6.

2.6.3. Emerson Crumb Test

The results of Emerson Crumb Test in Fig 2.11 show untreated loess-colluvium soils from Whaka Terrace are moderately to highly dispersive (class 3 to 4, Table 2.5). The results from the Modified Crumb Test (Table 2.5) indicate that the addition of 1% by weight of hydrated lime and quicklime to the loess-colluvium sample after 14 days moist curing produces non-dispersive soil (class 1), while the application of 1% by weight of gypsum does not appear to improve the dispersive behavior of the untreated sample (class 3-4). However, by increasing the concentration of gypsum to the 2% level a reduction in soil dispersiveness was observed (class 2). Furthermore, application of 4% gypsum produces a non-dispersive soil (class 1). Test results in Table 2.5 further indicate that the results of Emerson Crumb Test (1967) and the Modified Crumb Test (Sherard et al 1976) are comparable, but that Sherard's classification has the advantage of greater simplicity due to excluding slaking and swelling as criteria, and also by testing samples at their in-situ moisture content.

2.6.4. Pinhole Test

The following conclusions can be drawn from the test results(Table 2.6):

1) The in-situ and recompacted field samples are highly erodible (Fig 2.12). However, the data suggest that recompacted samples

Table 2.5 Dispersivity of field and stabilised samples.

TYPE OF STABILISER	EMERSON CLASS	MODIFIED EMERSON CLASS	REMARKS
NOT CURED	1-2 *	3-4 *	*Moderately to highly dispersive
0%			
MOIST CURED	1-2	3-4	
0%			
GYPSUM			
1%	1-2	3-4	
2%	1-2	2 *	*Slightly dispersive
4%	4 *	1	*No dispersion but swelling & slaking
QUICKLIME			
1%	8 *	1 *	*No dispersion, no swelling & slaking
2%	8	1	
4%	8	1	
HYDRATED LIME			
1%	8	1	
2%	8	1	
4%	8	1	
PORTLAND CEMENT			
2%	4	1	
4%	7 *	1	*No dispersion but swelling
GYPSUM+HYDRATED LIME			
2%	4	1	
4%	7	1	

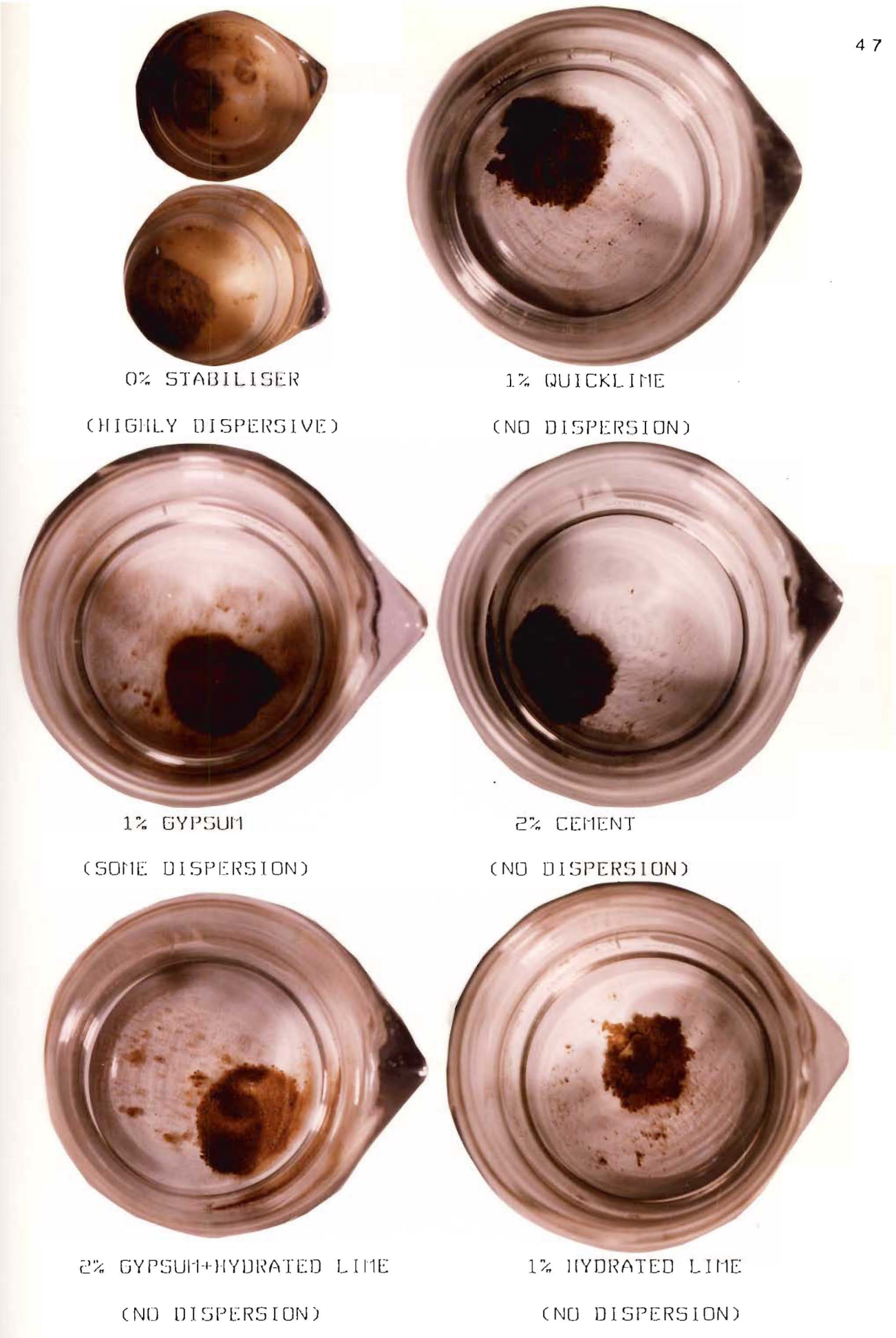
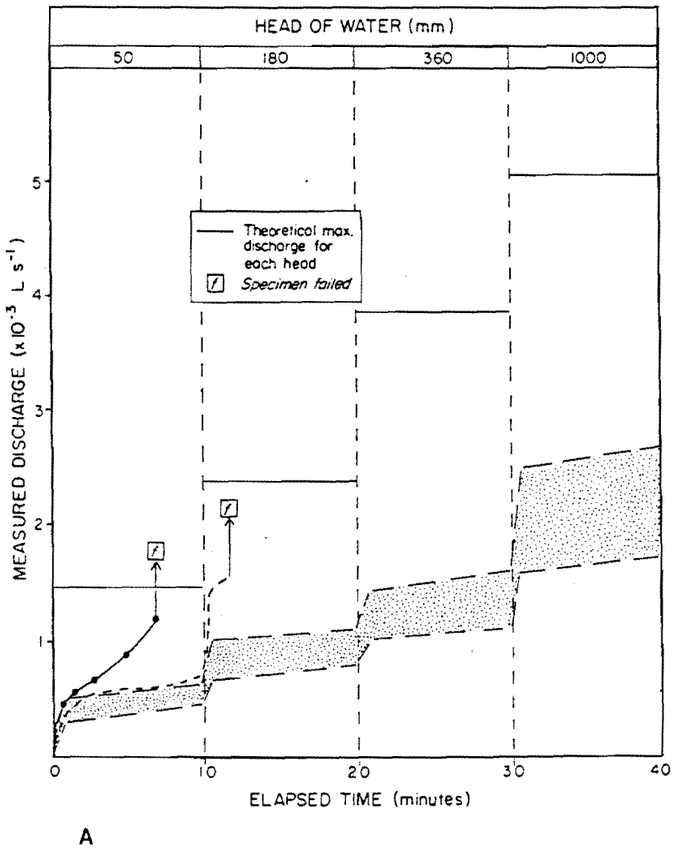
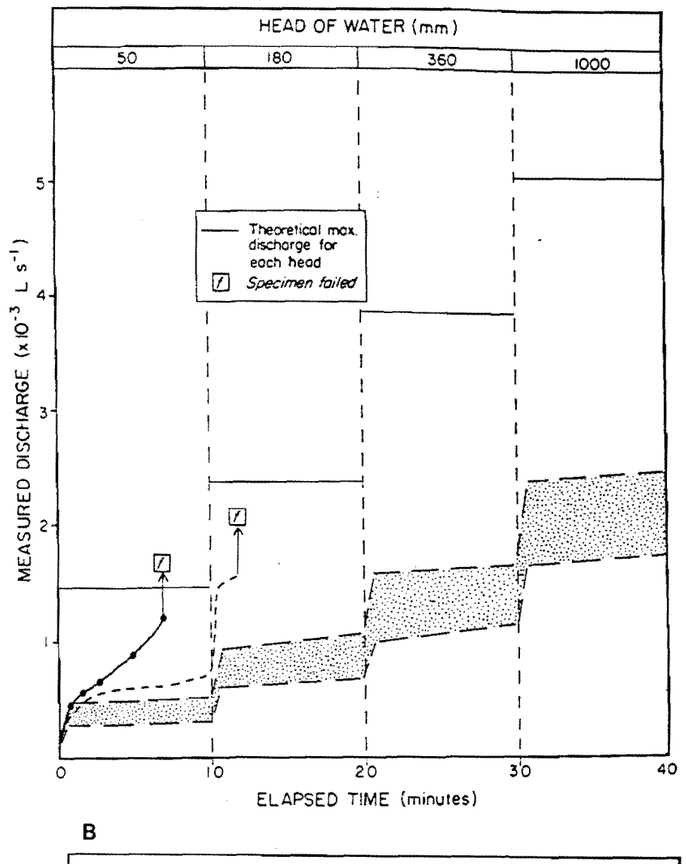
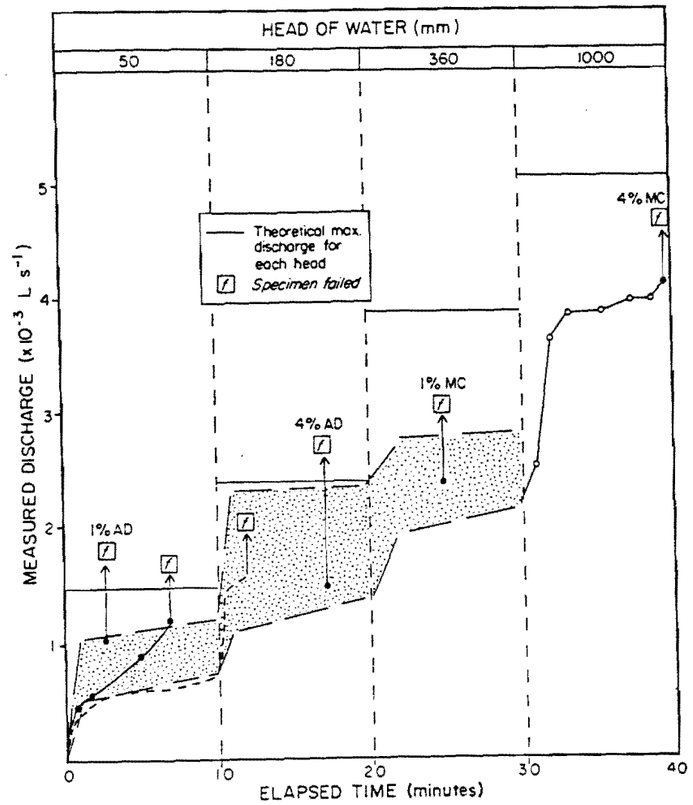


Fig 2.11 Emerson Crumb Test for treated & untreated samples







MC = Moist cured 14 Days Moist Cured Samples AD = Air dried

PINHOLE ERODIBILITY TEST (flow/time graph)

- in-situ (field sample)
- recompacted and cured (% O stabilizer)
- envelope for 1-4 % stabilizer

NOTE

1. Samples compacted at OMC in a single layer, following NZ Std 4402
2. Test result are the average of two tests per sample

Figure 2.12: Erodibility of treated and untreated samples: A - hydrated lime, B - quicklime, C - gypsum, D - cement, E - gypsum and hydrated lime

Table 2.6 Pinhole tests data for field and stabilised samples.

TYPE OF STABILISER	CURING CONDITION ml/s HEAD ml/s	FlOW RATE AT FAILURE AT 1000 mm	AVERAGE OF FLOW RATE	ERODIBILITY CLASS
0%	NOT CURED	1.2	-	E-50
0%	MOIST CURED	1.7	-	E-180
GYPSUM				
1%	MC *	2.7	-	E-360
1%	AD **	1.0	-	E-50
2%	MC	2.2	-	E-180
2%	AD	1.0	-	E-50
4%	MC	4.1	-	E-1000
4%	AD	0.9	-	E-180
QUICKLIME				
1%	MC	-	2.7	NE
1%	AD	-	2.1	NE
2%	MC	-	2.3	NE
2%	AD	-	2.6	NE
2%	WD ***	-	2.0	NE
4%	MC	-	1.3	NE
4%	AD	-	2.0	NE
4%	WD	-	2.1	NE
HYDRATED LIME				
1%	MC	-	2.1	NE
1%	AD	-	1.9	NE
2%	MC	-	1.9	NE
2%	AD	-	1.8	NE
2%	WD	-	1.8	NE
4%	MC	-	1.0	NE
4%	AD	-	1.2	NE
4%	WD	-	1.8	NE
P-CEMENT				
2%	MC	-	2.5	NE
2%	AD	-	2.6	NE
4%	MC	-	1.8	NE
4%	AD	-	1.3	NE
4%	WD	-	1.7	NE
GYPSUM+H LIME				
2%	MC	-	2.8	NE
2%	AD	-	2.4	NE
2%	WD	-	1.3	NE
4%	MC	-	1.7	NE
4%	AD	-	1.4	NE
4%	WD	-	1.9	NE

* MC= MOIST CURED
** AD= AIR DRIED
*** WD= WETTED AND DRIED

show slightly greater resistance against erosion, failing at a head of 180 mm in contrast to in-situ samples which failed at a head of 50 mm.

2) The application of 1% hydrated lime or quicklime (by weight of dry soil) to loess produces non-erodible material (Figure 2.12 A and B) which is in agreement with previous research by Evans (1977), Evans and Bell (1981), and Glassey (1986) using hydrated lime.

3) At higher percentage of quicklime or hydrated lime the flow rate significantly reduces until at 4% application of stabiliser, the flow rate under 1000 mm head, (1.1 mls^{-1}) is similar to the flow rate observed for untreated sample (Table 2.6.) under 50 mm head (1.2 mls^{-1}).

4) The application of gypsum has almost no effect on the erodibility characteristics of loess soil (Table 2.6). However, moist curing condition produces a slightly higher resistance against erosion at all concentrations (Fig 2.12c).

5) Data suggests that the application of Portland cement and a mixture of hydrated lime and gypsum to loess soil has a similar effect on erodibility to quicklime and hydrated lime (Figs, 2.12d and e).

6) With the exception of gypsum, all stabiliser agents produce non-erodible samples at 1-2% concentration, regardless of the curing condition.

2.7. Slaking

2.7.1. Terminology and Test Methods

Soil slaking refers to the processes involving the disintegration and collapse of the soil skeleton during saturation or immersion in water. Many factors contribute to soil slaking, including:

1) The magnitude of stresses resulting from release of trapped air which results from water drawn into soil pores under capillary forces, and the build up of increased air pressure which forces the soil skeleton to disaggregate. [Capillary forces are controlled particularly by soil pore size and permeability. Small pore size and low permeability create high capillary forces.]

2) Clay fraction and organic content, a high clay percentage and / or a high organic content increasing the cohesive properties of the soil skeleton.

3) Clay mineralogy

4) Initial moisture content

The durability of Port Hills loess has been assessed by Yetton, (1986) and Glassey (1986) using the Jar Slake and the Slake Durability Tests. Results from Yetton's work suggests that the Slake Durability Test is inadequate for the determination of slaking properties of lime-treated and cement-treated samples, because of complete destruction after the first cycle by abrasion. Consequently, the Jar Slake Test is thought to provide a more reasonable indication of slaking properties of Port Hills loess. The research by Glassey indicates that some slaking occurs to the soil treated with 1% and 2.5% hydrated lime, and that slaking is minimised with the application of 5% hydrated lime.

In this study the recompacted field sample and stabilised loess-colluvium samples were subjected to 5 cycles of wetting and drying (1 cycle consists of 4 hours wetting and 20 hours of drying at room temperature). The test procedure is outlined in appendix 7 and the data are summarised in Table 2.7.

2.7.2. Untreated Sample

The result indicates that untreated loess soil slakes soon after immersion in water, and has completely slaked at the end of the first cycle (Fig 2.13). The high slaking potential of Whaka Terrace loess-colluvium can be related to 1) the presence of high percentage of silt (75 to 77%) and relatively small pore sizes (as suggested by the low permeability and low porosity) which provides higher magnitude of stresses resulting from release of trapped air during saturation, and 2) low cohesive properties of the soil as suggested by grainsize analysis (12-14% clay).

2.7.3. Treated Samples

Jar Slake Test results (Table 2.7) indicated that the application of 1% hydrated lime and quicklime (by weight of dry soil) produces a durable material which sustains 5 wetting and drying cycles (JI=6). However, quicklime stabilised samples possess higher wetting and drying index than hydrated lime (Table 2.7 and Appendix 7). Durability of stabilised samples is firstly due to 1) flocculation and aggregation of soil particles, resulting in larger pore size and consequently lower air pressures upon saturation; 2) the alteration of soil dispersive properties with respect to change in chemical

A- Prior to testing

B- After testing

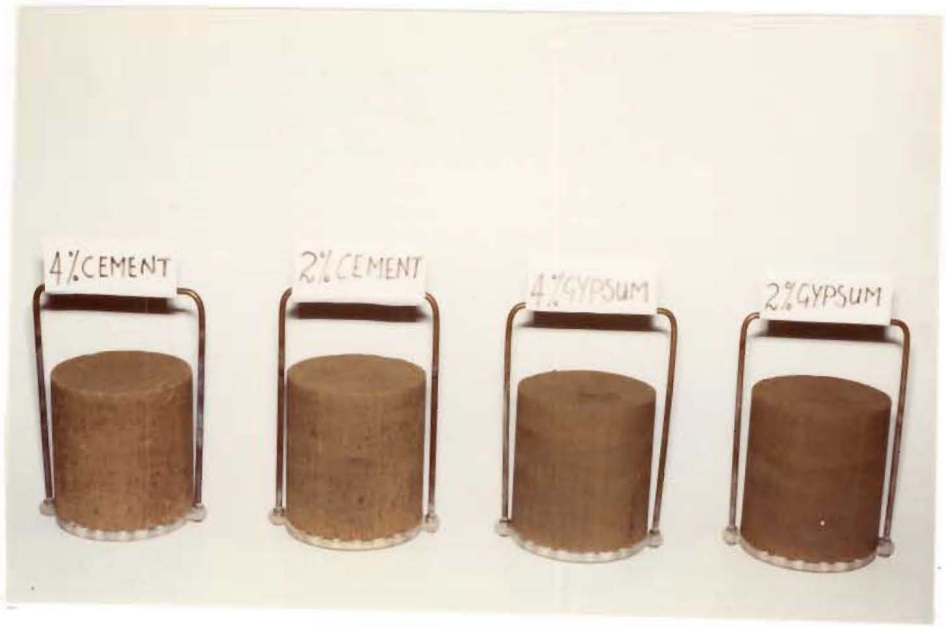
Fig 2.13 Jar Slake Tests for untreated and 1% stabilised samples.

Table 2.7 Slaking Indices for recompacted field and stabilised samples.

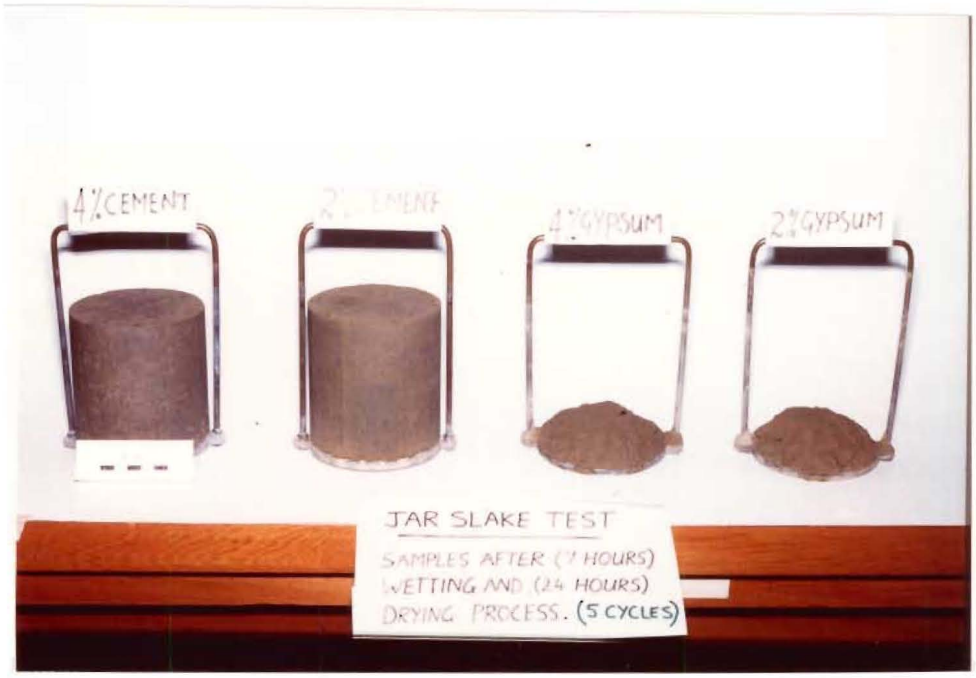
TYPE OF STABILISER	JAR SLAKE INDEX (J_I)	WETTING AND DRYING INDEX (W/D_I)
UNTREATED		
SAMPLE (0%)	1*	12%
GYPSUM		
1%	1	13.1%
2%	1	14.0%
4%	1	13.8%
QUICKLIME		
1%	6 **	99.3%
HYDRATED LIME		
1%	6	93.8%
PORTLAND CEMENT		
1%	1	15.2%
2%	6	98.7%
4%	6	99.3%
GYPSUM + HYDRATED LIME		
1%	1	14.0%

* Degrades into a pile of flakes or mud (completely slake)

** No change (durable material)



A- prior to testing



B- After testing

Fig.2.14 Jar Slake Tests for 2% and 4% cement & gypsum stabilised samples.

(Note: Refer to Fig 2.13 for untreated control)

composition of clay minerals and pore water salt (chapter 4); and 3) the crystallisation of cementing agents, enabling the soil skeleton to sustain positive pore pressure during immersion in water.

The application of 1% gypsum, Portland cement and a mixture of gypsum and hydrated lime fails to produce durable material, with samples completely slaked after the first cycle of wetting and drying (Fig 2.13). At higher concentrations of Portland cement (2-4%) samples do not produce any slaking and were able to sustain five wetting and drying cycles (Fig 2.14 and Table 2.7). Gypsum, however, failed to produce durable materials even at higher concentration, (2-4%) as shown in Figure 2.18 .

Finally, the result of this study indicates that slaking is minimised with the application of 1% quicklime and 2% hydrated lime . This result contrasts with Glassey (1986), who suggests that 5% application of hydrated lime required to minimise slaking. This may be related to the 7% higher percentage of clay fraction in his sample relative to sample tested in this study.

2.8. Swelling

2.8.1. Test Methods and Results

In this study Confined Uniaxial Swelling Test has been used to assess expansion of in-situ, untreated and treated recompacted samples. The test procedure is outlined in Appendix 8 and the test results are illustrated in Fig 2.15 and a summary of data is given in Table 2.8. The results are discussed below, and are based on an average of 4 to 6 tests per sample.

2.8.2. Field Samples

The uniaxial swelling strain data (Table 2.8) indicates that the untreated uncured recompacted sample and untreated recompacted 14 days moist cured samples have (14 and 18% swelling strain values respectively.

The results of grainsize analyses (section 2.3.1) show that samples have a high silt fraction and low clay content. Moreover, the study of clay mineralogy of Whaka Terrace loess by X-Ray diffraction (Fig 4,4) indicates that clay minerals are non-expandable type (e.g. illite, kaolinite and non-swelling Fe-chlorite). Therefore, the expansion of the untreated and recompacted loess-colluvium sample

appear to be the result of slaking pressure, rather than the swelling of clay minerals. This conclusion is further supported by the fact that untreated recompacted samples after 7 days moist curing and 7 days air drying show a two fold increase in swelling relative to that of untreated moist cured samples. This result is a reflection of the increase in slaking pressure in air dried samples after immersion in water during the test. For samples that were subjected to 7 days moist curing, followed by 7 days wetting and drying complete disintegration of the soil skeleton was observed, which meant that the test could not proceed.

2.8.3. Stabilised Samples

The research results (Table 2.9) indicate that the addition of hydrated lime to moist soil reduces significantly its swelling potential.

2.8.3.1. Moist Cured Samples

Figure 2.15 (a) shows that with the application of 1% to 2% hydrated lime by weight of dry soil the swelling potential of loessial soil after 14 days moist curing reduces from 14% to 3.5% and 2.5% respectively. Swelling potential is minimised to less than 1% with the application of between 2 and 4% hydrated lime. These results are supported by the research of Brandl (1981), and Evans and Bell (1981), but disagree with those of Glassey (1986), who suggests that 7.5 to 10% concentration of hydrated lime addition are required to minimise swelling potential. The reduction in swellability of quicklime and hydrated lime-treated samples can be attributed to a decreased affinity for water of the calcium saturated clay (in which substitution of Ca cations for Na or K cations occurs due to lime reaction with clay minerals), and the formation of a cementitious matrix which resists volumetric expansion.

The effect of the application of quicklime and Portland cement on the swelling potential of the loess-colluvium soils is similar to that of hydrated lime (Fig 2.15). In addition, the data suggests that there is no reduction in swellability of loessial soil resulting from the application of 1 to 4% gypsum (Fig 2.15 a). The application of a mixture of gypsum and hydrated lime is similar to the effect of hydrated lime addition (Table 2.9).

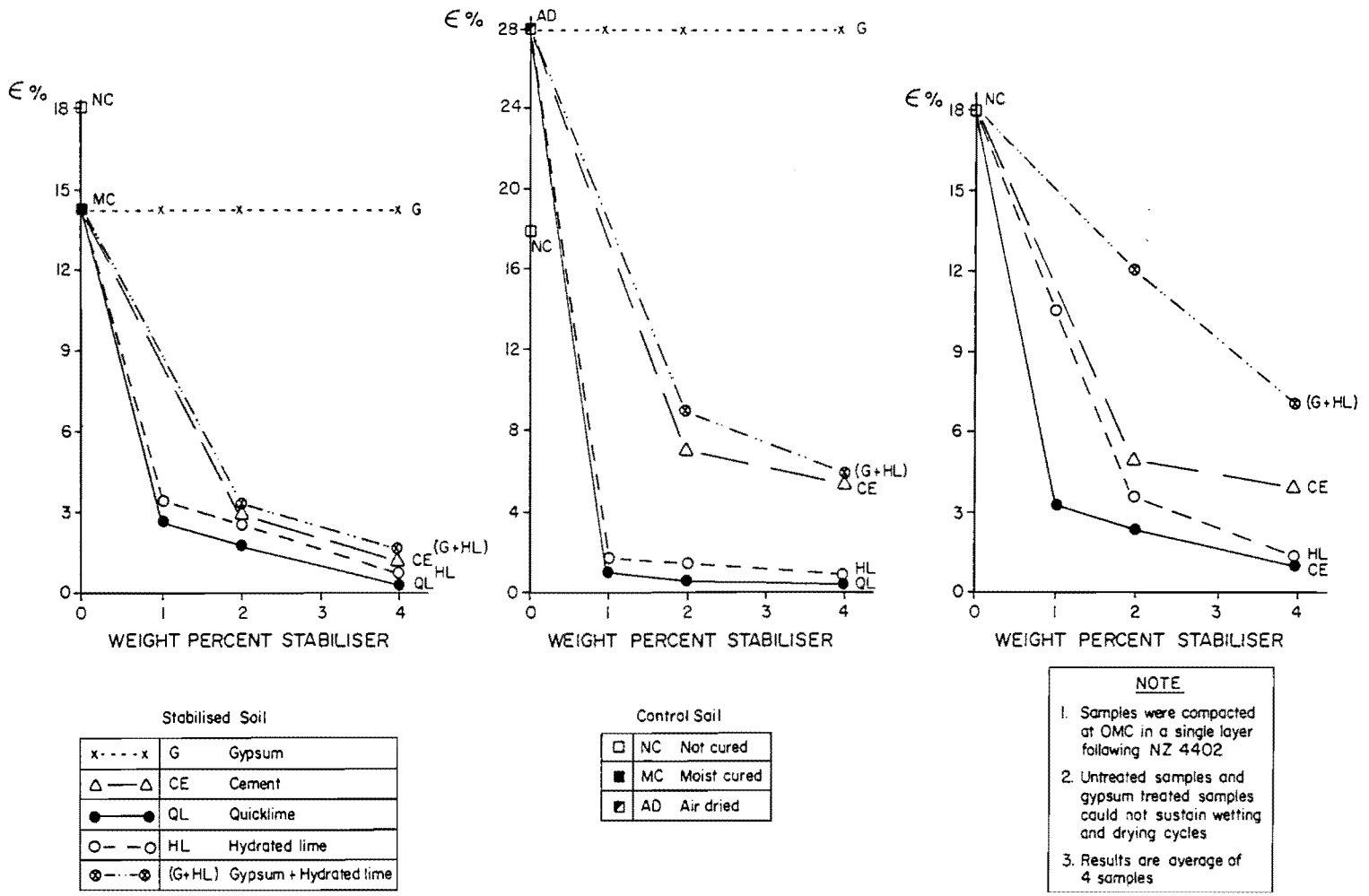


Figure 2.15: Swellability of natural and stabilised loess

Table 2.8. Uniaxial Swelling Strain data for field and stabilised samples.

STABILISER & CURING TYPE	SWELLING STRAIN STRAIN VALUE (%)	BULK-DENSITY tM^{-3}	DRY-DENSITY tM^{-3}	MOISTURE CONTENT w%
UNTREATED NOT CURED 0%	18%	-	-	-
UNTREATED * MC - 0%	14%	2.1	1.9	11.3
UNTREATED ** AD - 0%	28%	2.06	1.87	10.0
UNTREATED *** WD - 0%	ND *X	2.1	1.9	11.0
GYPSUM				
1% - MC	14%	2.01	1.74	15.3
1% - AD	28%	2.01	1.74	15.3
1% - WD	ND	2.01	1.74	15.3
2% - MC	14%	1.90	1.64	15.3
2% - AD	28%	1.90	1.64	15.3
2% - WD	ND	1.90	1.64	15.3
4% - MC	14%	2.20	1.86	17.4
4% - AD	28%	2.20	1.86	17.4
4% - WD	ND	2.20	1.86	17.4
QUICKLIME				
1% - MC	2.8%	1.89	1.65	14.7
1% - AD	1.0%	1.89	1.65	14.7
1% - WD	3.2%	1.89	1.65	14.7
2% - MC	1.9%	1.94	1.62	19.9
2% - AD	0.7%	1.94	1.62	19.9
2% - WD	2.3%	1.94	1.62	19.9
4% - MC	0.2 %	1.91	1.56	22.4
4% - AD	0.5%	1.91	1.56	22.4
4% - WD	1.0%	1.91	1.56	22.4
HYDRATED LIME				
1% - MC	3.5%	2.03	1.80	13.0
1% - AD	1.7%	2.03	1.80	13.0
1% - WD	10.5%	2.03	1.80	13.0
2% - MC	2.5%	2.05	1.73	18.5
2% - AD	1.6%	2.05	1.73	18.5
2% - WD	3.5%	2.05	1.73	18.5
4% - MC	0.7%	1.99	1.62	22.5
4% - AD	0.5%	1.99	1.62	22.5
4% - WD	1.0%	1.99	1.62	22.5
P - CEMENT				
2% - MC	2.0%	1.95	1.65	18.3
2% - AD	7.0%	1.95	1.65	18.3
2% - WD	5.0%	1.95	1.65	18.3
4% - MC	1.1%	1.92	1.56	23.1
4% - AD	5.5%	1.92	1.56	23.1
4% - WD	4.0%	1.92	1.56	23.1
GYPSUM+H LIME				
2% - MC	3.5%	2.07	1.78	16.4
2% - AD	9.0%	2.07	1.78	16.4
2% - WD	12.0%	2.07	1.78	16.4
4% - MC	1.2%	1.99	1.63	21.4
4% - AD	5.7%	1.99	1.63	21.4
4% - WD	7.0%	1.99	1.63	21.4

* MC = MOIST CURED
** AD = AIR DRIED
*** WD = WETTED & DRIED
* X ND = NOT DETERMINED

2.8.3.2. Air Dried Samples

Figure 2.15 (b) illustrates that lime treated, air dried samples have a lower swelling potential than moist cured samples. For example, at 1% quicklime addition moist cured samples have a swelling strain value of 2.8%, while with an equal amount of quicklime air dried samples have swelling strain values of around 1% . Possibly this extra reduction in swelling of air dried samples is due to carbonation of lime after exposure to the atmosphere.

On the other hand gypsum, cement and a mixture of gypsum and hydrated lime stabilised, air dried samples have higher swelling potentials than the moist cured samples (Fig 2.15b). For example, loess-treated samples with 2% and 4% cement after 14 days moist curing have 2% and 1% swelling strain value, while air dried samples have swelling potential of 7% and 5.5% respectively. This indicates that for cement-treated samples 7 days moist curing prior to air drying is not enough time to form reaction products (hydrated calcium silicates and aluminates) which reduce the swelling strain potential.

2.8.3.3. Wetted and Dried Samples

Figure 2.15 (c) suggests that wetted and dried hydrated lime treated samples at low concentration of stabiliser (1 and 2%) have higher swelling potential than moist cured and air dried samples. The application of quicklime illustrates similar trends to those of hydrated lime, although the samples treated with quicklime possess lower swelling strain value. For example 1 and 2% quicklime-treatd samples possess 3.2-2.3% swelling strain values while, samples treated with 1 and 2% hydrated lime show 10.5-3.5% swelling. With the application of 2 to 4% cement swelling is reduced but this reduction is less than the reduction obtained for moist cured samples,(Fig 2.15c).

Gypsum-treated samples cannot sustain the wetting and drying cycles and all samples disintegrated prior to the testing. With the application of 2 to 4% mixed gypsum and hydrated lime, the swelling strain of the stabilised sample is reduced, but the results are less pronounced than those obtained with the pure hydrated lime (Fig 2.15c).

In summary, it can be concluded that:

1) of those stabilisers tested, quicklime has the greatest potential to reduce swelling of the untreated loess soils.

2) The application of cement significantly reduces the swelling potential of loessial soil after 14 days moist curing.

However, air dried samples, and wetted and dried samples still possessing high swelling potential after 2 to 4% cement addition (Fig 2.15).

3) Gypsum has no effect on reducing swelling characteristics of loess-colluvium soils. However, gypsum-treated samples after 14 days moist curing produce lower swelling values than gypsum-treated air-dried samples. This result follows the trend also observed for gypsum-treated moist cured samples that were tested for erodibility (see section 2.6.4).

4) The data suggests that for the moist curing condition, the application of a mixture of hydrated lime and gypsum (1:1 ratio) is comparable with the effects of equal amounts of pure hydrated lime addition (Fig 2.15). However, air-dried and wetted-and-dried samples of the gypsum and hydrated lime mixture did not produce satisfactory results with respect to reduction of swelling potential.

5) Curing conditions have an additional effect of suppr-essing the swelling potential of loess soils, data suggesting that;

a) The wetting and drying curing condition has the least effect on reducing swelling potential for all types and concentrations of stabilisers used.

b) For lime treated samples the air dried curing condition most effectively reduces swelling potential. For cement, gypsum, and the mixture of hydrated lime and gypsum the moist curing condition was more effective than air drying, and wetting and drying in reducing swelling potential.

6) In the Port Hills shrink/swell behavior of loess soils is an important factor in tunnel gully development (Fig 1.5). There is therfore, a great advantage in the use of chemical stabilisers (particularly quicklime and hydrated lime) for controlling volume stability of the soil.

2.9. Synthesis

Laboratory investigations have indicated that chemical stabilisation techniques can be successfully used to change dispersive/erosive characteristics of loess soil.

With regard to soil index properties;

1) The application of quicklime, hydrated lime, Portland cement and a mixture of gypsum and hydrated lime (1:1 ratio) results in an increase in the optimum moisture content and a decrease in the

maximum dry density . Application of gypsum has no appreciable effect on moisture content / dry density relationship of loessial soils.

2) Grainsize analysis results indicate that there is an increase in the sand size fraction of soil samples (with a corresponding decrease in silt and clay fraction) for all of the stabilisers used. The effect is greatest for soils treated with quicklime, and least for soil treated with gypsum.

3) With the exception of gypsum, the application of 1-2% stabilisers increases the plastic index of all samples and decreases the plastic index of samples for 2-4% application of stabiliser. The effect is most pronounced for quicklime and Portland cement treated samples.

4) The application of quicklime, hydrated lime, Portland cement and mixed stabiliser, increases soil permeability with a corresponding decrease in saturated bulk density. Gypsum, has only a very.limited effect.

With regard to soil physical properties;

1) Application of hydrated lime and quicklime provides a non-dispersive, non-erodible and durable material.

2) The effect of Portland cement on the dispersion, erosion, slaking and swelling potential of the loess-colluvium soils is similar to that of hydrated lime and quicklime, although satisfactory results can only be achieved by using higher concentrations of cement than is required for the use of the lime stabilisers.

3) Application of gypsum has very little or no effect on dispersion, erosion, slaking and swelling potential of untreated loess, and failed to provide any satisfactory results.

4) A mixture of gypsum and hydrated lime in a 1:1 ratio produces a non-dispersive and non-erodible material, but it cannot produce non-swelling and non-slaking samples. Therefore there is no benefit achieved from mixing the two stabilisers, because application of hydrated lime by itself provides more satisfactory results than the mixture.

CHAPTER THREE: STRENGTH CHARACTERISTICS

3.1 Introduction

Short-term (1-7 day) strength gain in lime and cement stabilised soils is a result of cation exchange, flocculation and agglomeration of clay minerals (Neubauer and Thompson, 1972), while longer term the formation of pozzolanic products (cementitious agents) is considered to be the source of strength gain (Croft, 1964). The interlocking of these new mineral growths (calcium hydrated silicates and aluminates) in stabilised soils increases the bonding between soil particles, as a result of which the soil skeleton behaves as a more rigid and brittle material and is better able to resist deformation by shear forces and normal forces.

The extent of strength gain in mixtures of moist soil with lime or cement is dependent on many factors, which include;

a) Soil type (Herrin and Mitchell, 1961 ; Ingles and Metcalf, 1973).

b) Type of stabiliser (Lu et al, 1957 ; Wang et al, 1963 ; Alexander et al, 1972).

(c) Percentage of stabiliser (Neubauer and Thompson, 1972; Brandl, 1981).

(d) Compaction history, such as; i) moulding moisture content (Remus and Davidson, 1961; and Davidson et al, 1962). ii) time between mixing and compaction (Arman and Saifan, 1967). iii) Compaction techniques (Remus and Davidson, 1961).

(e) Curing condition, such as; i) curing time (Laguros et al, 1956; and Croft, 1964) ii) availability of moisture and temperature (Herrin and Mitchell, 1961; Andy, 1963; Metcalf and Ingles, 1973.

In this study the strength characteristics of recompacted untreated and chemically stabilised soil were studied using the unconfined compressive strength test and undrained shear box test. Unconfined Compressive strength tests were carried out to assess strength gain and stress/strain relationships for untreated samples and chemically stabilised samples, while undrained shear box tests were carried out with the aim of:

a) To determine the peak undrained shear strength parameters (c and ø) of the recompacted untreated loess sample to provide a basis for comparison with shear strength properties of chemically stabilised samples.

b) To evaluate the effectiveness of each chemical stabiliser on improving the shear strength of stabilised sample.

3.2. Unconfined compressive strength

3.2.1. Test Methods and Results

Unconfined compressive strength tests were carried out using a Wykeham-Farrance 10000 kg stepless loading frame, and the test procedure is outlined in Appendix 9. The untreated and chemically stabilised samples were compacted at optimum moisture content using New Zealand Standard 4402 (Appendix 2), prior to 14 days moist curing at 20° C and 99% relative humidity.

Unconfined compressive strength values given for untreated samples are the average of 5 samples tested, while values for stabilised samples are the average of 2 or 3 samples. The loading rate for all samples was constant at 0.5 mm per minute. Stress and strain at peak value for untreated and chemically stabilised samples were measured, and the results are presented in Fig 3.1 and 3.5 respectively. A summary of test data is given in Table 3.1.

Figure 3.4 illustrates the relationship between density and unconfined compressive strength, while the stress/strain behavior of treated and untreated samples during unconfined uniaxial compression is shown in Fig 3.6. The modulus of elasticity (E_{50} - tangent method) for the control and stabilised samples was calculated (Brown, 1981), and the results are summarised in Fig 3.7. The unconfined compressive strength test results are discussed in greater detail below.

3.2.2. Untreated Samples

The test results indicate that the unconfined compressive strength of the untreated samples (uncured and 14 days moist cured) is 190-210 kPa, (Table 3.1). In addition, the test data suggests that the strength of the untreated samples after 14 days moist curing has increased by 10% relative to the untreated uncured samples. This slight increase in strength is possibly due to the more homogeneous distribution of moisture in the sample after 14 days curing relative to moisture distribution in the uncured sample. This result does not agree with that of Glassey (1986), who found that the strength of the untreated sample increased by almost 100% after 14 days moist curing.

3.2.3. Strength Gain

3.2.3.1. Hydrated Lime treated Samples

Figure 3.1 shows that application of 1% by weight of hydrated lime increases the unconfined compressive strength of stabilised samples, from 210 kPa for untreated samples, to 350 kPa for stabilised samples. Strength gain is maximised at a 2% application of hydrated lime with a strength increase of 3 times, relative to that of the untreated samples (Table 3.1). With the application of a higher concentration of stabiliser (4%), a reduction in strength gain can be observed (Fig 3.1).

The trend observed in the results from this study (Fig 3.1) is in agreement with the trends observed by Evans and Bell (1981), and Glassey (1986) (Figs 3.2 and 3.3) in that unconfined compressive strength increases with the application of 1% and 2% hydrated lime addition, which is followed by a reduction at higher concentrations of stabiliser. However, Evans and Bell (1981) found that strength of loess soil is maximised at 5% concentration of hydrated lime, whereas Glassey's (1986) results indicate that strength of hydrated lime treated samples is minimised at 5% and maximised at 7.5%.

3.2.3.2. Quicklime-treated Samples

The test results (Table 3.1) indicate that the application of quicklime to Port Hills loess has a similar trend to that of hydrated lime. However, 1% and 4% quicklime-treated samples have greater strength than hydrated lime treated samples (Fig 3.1). For example, unconfined compressive strength of samples treated with quicklime at 1% and 4% concentrations is 525 kPa and 306 kPa respectively, while at the same concentrations samples treated with hydrated lime show 350 kPa and 306 kPa respectively. The significant increase in lime-treated samples is due to production of cementing agents such as Tobermorite gel and CHS crystals, the mechanism of which is discussed in section 4.3.3.2. Furthermore, it can be observed that 4% quicklime-treated samples possess lower strength relative to those samples treated at 2% level. The reason for this is related to the presence of some unreacted lime "gel" around the edge of soil grains in 4% quicklime-treated samples which is discussed in section 4.3.3.2.

Table 3.1 Unconfined Compressive Strength Test Results.

TYPE OF STABILISER	UCS (kPa) (kPa)	STRAIN AT FAILURE (%)	MODULUS OF ELASTICITY (MPa)
NOT CURED			
0%	190	2.3	1.7
MOIST CURED			
0%	210	2.8	1.1
GYPSUM			
1%	285	2.3	25.0
2%	250	2.0	20.0
4%	255	3.8	9.0
QUICKLIME			
1%	525	1.3	60.0
2%	570	1.2	72.0
4%	390	1.7	32.0
HYDRATED LIME			
1%	350	1.6	35.0
2%	625	1.5	62.0
4%	306	2.2	15.0
PORTLAND CEMENT			
1%	320	1.2	32.0
2%	750	1.1	110.0
4%	250	3.7	10.0
GYPSUM+HYDRATED LIME (1:1 ratio)			
2%	550	1.8	37.5
4%	327	2.5	15.0

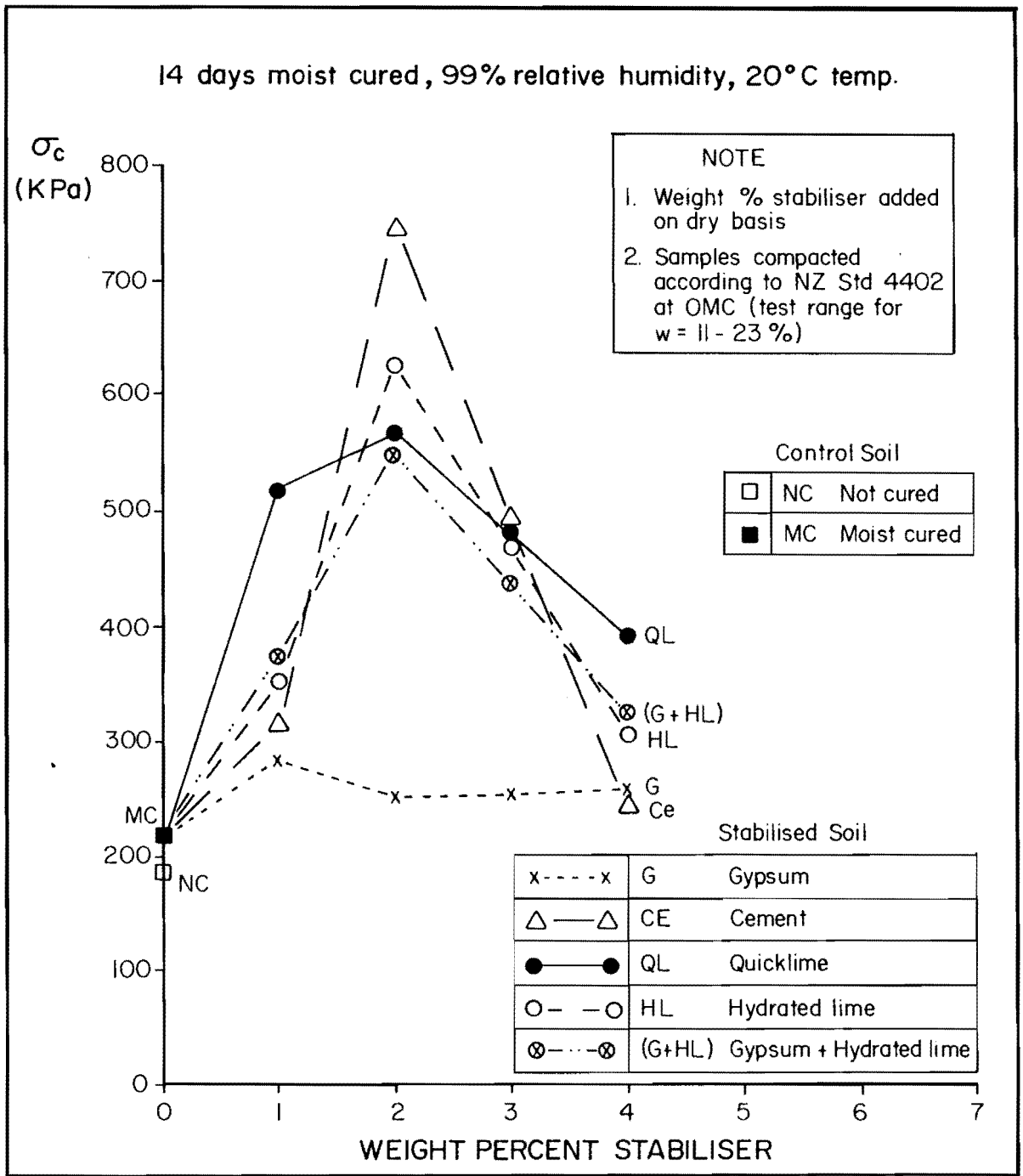


Figure 3·1: Unconfined compressive strength for natural soil and chemically stabilised samples

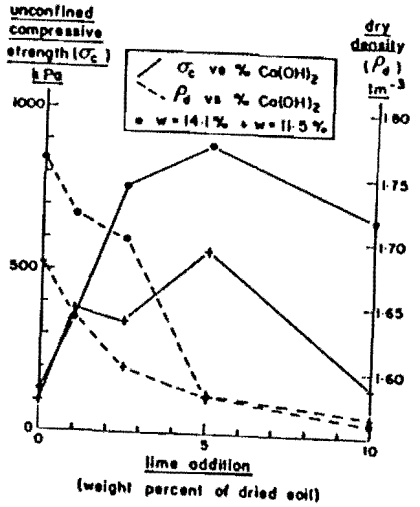


Fig. 3.2 Unconfined compressive strength and compacted dry density plots for lime additions to parent-loess, Port Hills (Evans and Bell, 1981).

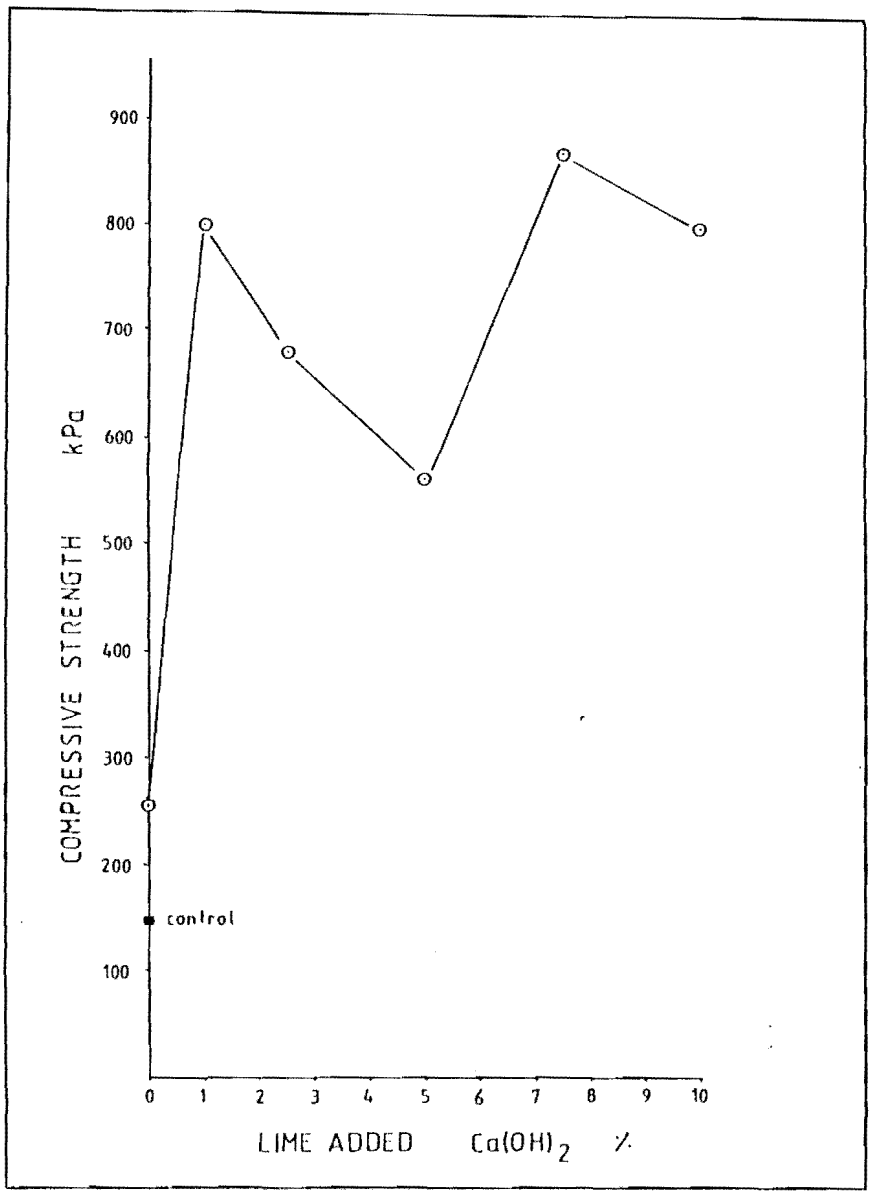


Fig. 3.3 Averaged maximum compressive strengths of the control sample, and lime treated samples, 14 days moist cured.

3.2.3.3. Cement-treated Samples

Figure 3.1 shows that application of 1% by weight of cement increases the strength of the stabilised sample from 210 kPa for untreated samples to 320 kPa for stabilised samples. With the addition of 2% Portland cement and after 14 days moist curing the strength of the stabilised samples increases to 750 kPa which is 4 times the strength values obtained for untreated samples, and is the maximum strength gain obtained for all stabilised samples tested. This significant increase in strength is related to the type and texture of pozzolanic products in cement stabilised samples, which are discussed in section 4.3.3.2.

The results (Table 3.1) indicate that there is a large reduction in compressive strength of 4% cement-treated samples relative to strength values obtained for the 2% cement-treated samples. This reduction follows the trend observed for other stabilised samples, but the size of the reduction (750 kPa to 250 kPa) for the cement stabilised samples is much larger than that observed for other types of stabilised samples between 2% and 4%. This is possibly related to the presence of a high moisture content (5% to 6% > OMC), which causes greater resistance against compaction resulting in lower density in the 4% cement treated sample (Trimer and Ross 1956, Ralling 1969).

3.2.3.4. Gypsum-treated Samples

. The test results indicate that application of gypsum has very little or no effect on the strength characteristics of untreated loess soil (Fig 3.1). A slight increase in the unconfined compressive strength from 210 kPa for untreated samples to 285 kPa for 1% gypsum-treated samples can be observed. This may be related to the flocculation of clay minerals in gypsum-treated samples resulting better interlocking of the grains present in the soil enabling slightly stronger resistance of the soil skeleton to the normal forces. However, no further increase in strength was achieved at higher concentrations of gypsum .

The lack of significant strength gain in gypsum treated samples is related to the lack of pozzolanic products (cementing agents) as suggested by the mineralogical study section 4.3.3.2).

Figure 3.1 also shows that the effect of the application of a mixture of hydrated lime and gypsum (1:1 ratio) is similar to that of hydrated lime, and there are no extra benefits obtained from mixing the

two stabilisers.

3.2.3.5. Principal Conclusions

1) Recompacted untreated loess-colluvium (cured and uncured) has low unconfined compressive strength (200 kPa).

2) Application of 2% by weight of Portland cement produces the greatest increase in the unconfined compressive strength of untreated soil, while quicklime treated samples produce the greatest strength gain at the 1% and 4% level.

3) Gypsum has little or no effect on the strength characteristics of loessial soil.

4) Strength gain in lime and cement-treated samples after 14 days moist curing is related to the flocculation of the clay minerals as well as to the formation of semi-crystalline pozzolanic products as shown in Figs 4.11 and 4.15, as a result of which bonding between the soil grains increases, resulting in the improvement in the cohesive properties of the soil skeleton and an increase in the unconfined compressive strength of stabilised samples.

3.2.4. Strength/Density Relationship

Figure 3.4 shows that quicklime, hydrated lime and cement treated samples at concentrations of 1-4% possess lower dry densities and higher compressive strength values relative to the untreated samples. The test results (Fig 3.4 a and c; Table 3.2) further indicate that for quicklime and hydrated lime the maximum compressive strength is obtained at the 2% level, which corresponds with the maximum dry density. Minimum compressive strength correlates with the 4% levels of stabiliser and samples possess lower dry density relative to the 1 and 2% level of application. Therefore, it can be seen that when strength gain is a prime objective of stabilisation, the field compaction at optimum moisture content for quicklime and hydrated lime treated soil is an important factor which should be considered.

Figure 3.4 (c) indicates that for the 4% cement-treated sample there is a reduction in strength values relative to the 2% cement-treated sample, and this correlates with a significant decrease in dry density of the 4% treated sample. At 2% by weight of cement the compressive strength value is greatest although it has a lower dry density relative to the 1% treated sample.

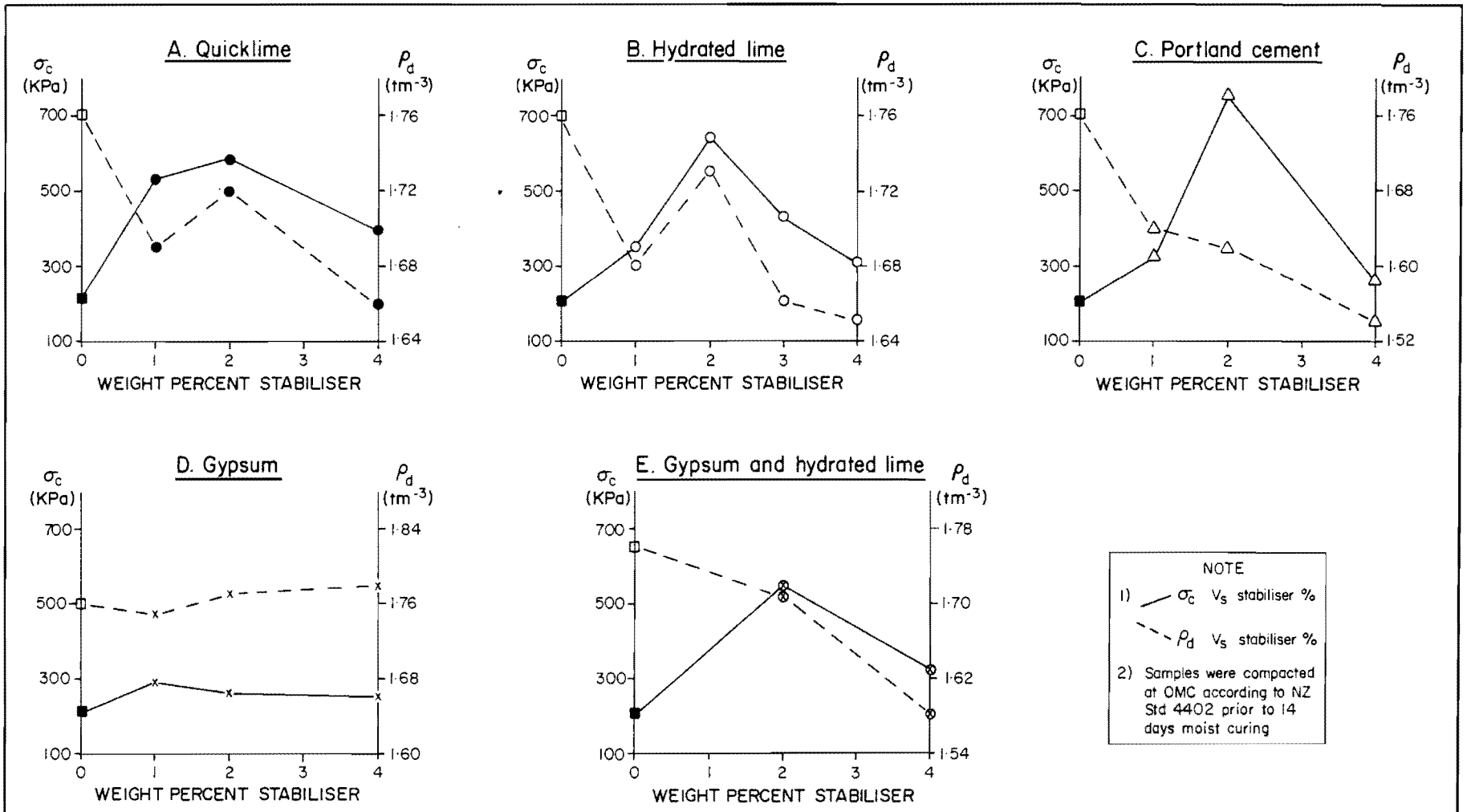


Figure 3·4 : Relationship between percentage of stabiliser used, dry density, and unconfined compressive strength

Figure 3.4 (d) shows gypsum does not produce significant changes in dry density and compressive strength relative to the untreated soil. The dry density and strength relationship for the mixed stabiliser (gypsum and hydrated lime) has a similar trend to that of the hydrated lime and quicklime treated samples (Fig 3.4 e), and show a maximum compressive strength at 2% which also correlates with the maximum dry density at 2% application of stabiliser.

The relationship between dry density and compressive strength of lime treated samples achieved in this study is in agreement with Remuset et al (1961); Herrin and Mitchell (1961); and Alexander et al (1972), but does not agree with Evans and Bell (1981) who found that compacted dry density decreases as unconfined compressive strength increases with increasing lime content. It seems that the reduction in the dry density of stabilised samples at 1% concentration of quicklime and hydrated lime is related to the flocculation effect of these stabilisers on clay particles in the soil, which increases the void ratio. The increase in dry density at the 2% concentration of lime is possibly the result of a greater concentration of cementing agents within the soil. The reduction in dry density at 4% level of stabilisers is related to the low reactivity of illitic soil with lime, as a result of which unreacted hydrated lime acts as a gel (as suggested by the SEM results section 4.3.3.2) which resists compaction, so that lower dry density and lower compressive strength values are obtained.

3.2.5. Strain At Peak Strength

Figure 3.5 illustrates that the strain values at peak strength for untreated samples (moist cured and uncured) are low, with an average of 2-3%. Test results also indicate that there is a reduction in strain values for all stabilised samples at concentrations of 1-2%. However, gypsum stabilised samples do not exhibit a significant reduction in strain. At 1% concentration, gypsum treated samples indicate a reduction of only 10-15% relative to the strain values observed for the untreated samples (Table 3.1).

With the application of 4% stabilisers all samples exhibit an increase in the strain values relative to that obtained at the 1% and 2% level (Fig 3.5), which is least for quicklime treated samples and greatest for cement and gypsum treated samples. The large increase in strain values observed for the 4% cement stabilised sample is probably

Table 3.2 Dry Density And Compressive Strength Values For Treated and Untreated Samples.

TYPE OF STABILISER	DRY DENSITY pd (tm^{-3})	MOISTURE CONTENT%	COMPRESSIVE STRENGTH VALUE (kPa)
MOIST CURED			
0%	1.76	11.0	210.0
GYPSUM			
1%	1.75	10.1	294.0
2%	1.76	11.4	263.0
4%	1.78	13.4	252.0
QUICKLIME			
1%	1.69	10.7	535.0
2%	1.72	13.4	590.0
4%	1.66	15.2	398.0
HYDRATED LIME			
1%	1.69	11.2	352.0
2%	1.73	15.0	643.0
4%	1.65	17.2	306.0
PORTLAND CEMENT			
1%	1.64	10.0	294.0
2%	1.62	12.8	750.0
4%	1.54	22.0	260.0
GYPSUM+HYDRATED LIME (1:1 ratio)			
2%	1.72	13.1	550.0
4%	1.58	21.0	326.0

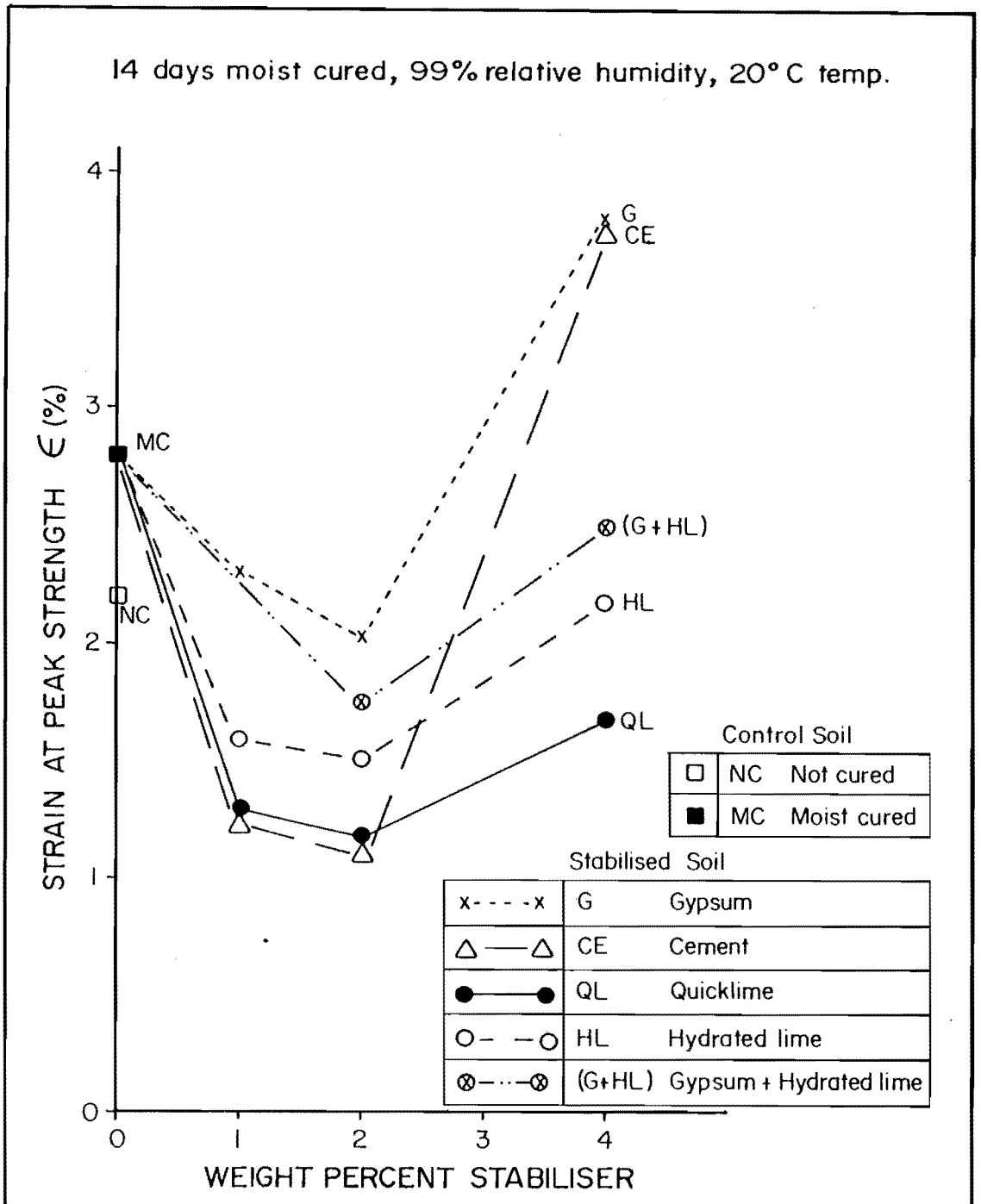


Figure 3·5 : Strain values at peak strength for natural and chemically stabilised soils

due to its higher moisture content (6% above OMC).

Figure 3.6 shows that the application of 1-2% quicklime, hydrated lime and cement to the untreated soil modifies it to a stronger and more brittle material. Furthermore, Figs 3.5 and 3.1 show that the reduction in strain values of chemically stabilised samples at 1-2% levels of concentration is comparable with the increase in unconfined compressive strength values of these samples. Furthermore, the maximum strain values observed occur in the 4% stabilised samples, which correlates with the minimum unconfined compressive strength values obtained. Finally, it can be concluded that minimum strain values for stabilised samples correlate with their maximum compressive strength values.

3.2.5 Stress/Strain Relationship

Figure 3.6 illustrates the effect of chemical stabilisers on the stress/strain properties of Whaka Terrace loess -colluvium. The results indicate that cement and lime treated samples possess a higher failure stress and lower strain deformation relative to the untreated samples, implying that the stabilised samples behave as a more brittle material. Fig 3.7 shows that untreated samples have a modulus of elasticity of 1-2 MPa, which is comparable with the results by Lee et al (1983) on silty soils and Glassey (1986) on loess soils.

The results (Fig 3.7) also indicate that the modulus of elasticity significantly increases with the application of 1-2% lime or cement. This increase is greatest for cement treated samples (65 x increase relative to the untreated samples).

A reduction in the modulus of elasticity can be observed in the 4% concentration for all stabilisers used. This reduction is least for quicklime treated samples and greatest for gypsum and cement-treated samples. However, the modulus of elasticity of 4% cement-treated samples is of the order of 10 times greater than those obtained for the untreated samples.

Test results (Fig 3.7) indicate that with a 1% application of gypsum the modulus of elasticity increases. This trend is followed by a reduction in the modulus of elasticity in the 2% and 4% gypsum treated samples. Fig 3.7 further shows that the modulus of elasticity at 1% and 4% concentrations is greatest for quicklime stabilised samples, while the modulus is optimized with the application of 2% by weight of Portland cement.

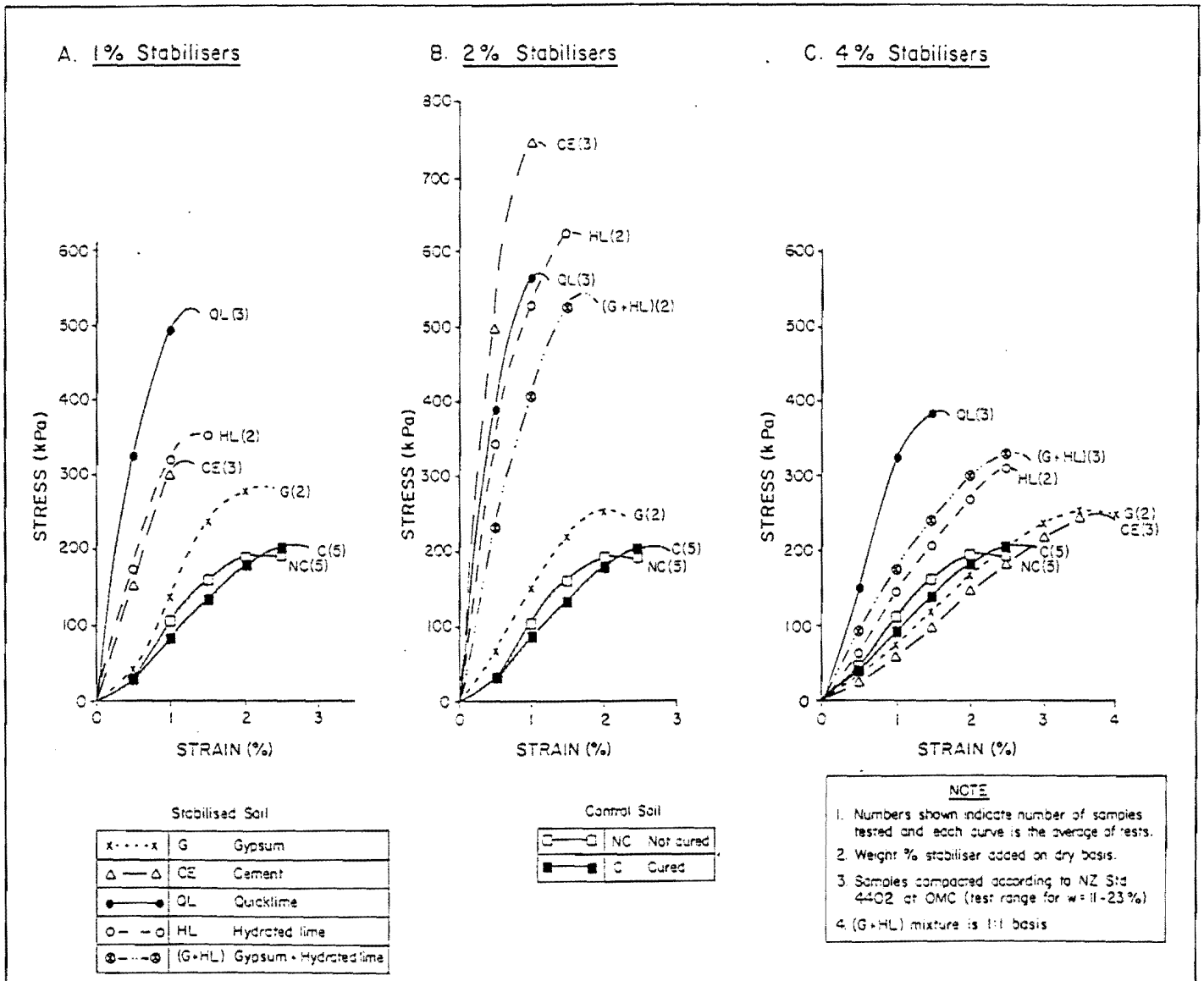


Figure 3·6: Stress/strain curves for natural soil and chemically stabilised samples (14 days moist cured, 99% relative humidity, 20° C temperature)

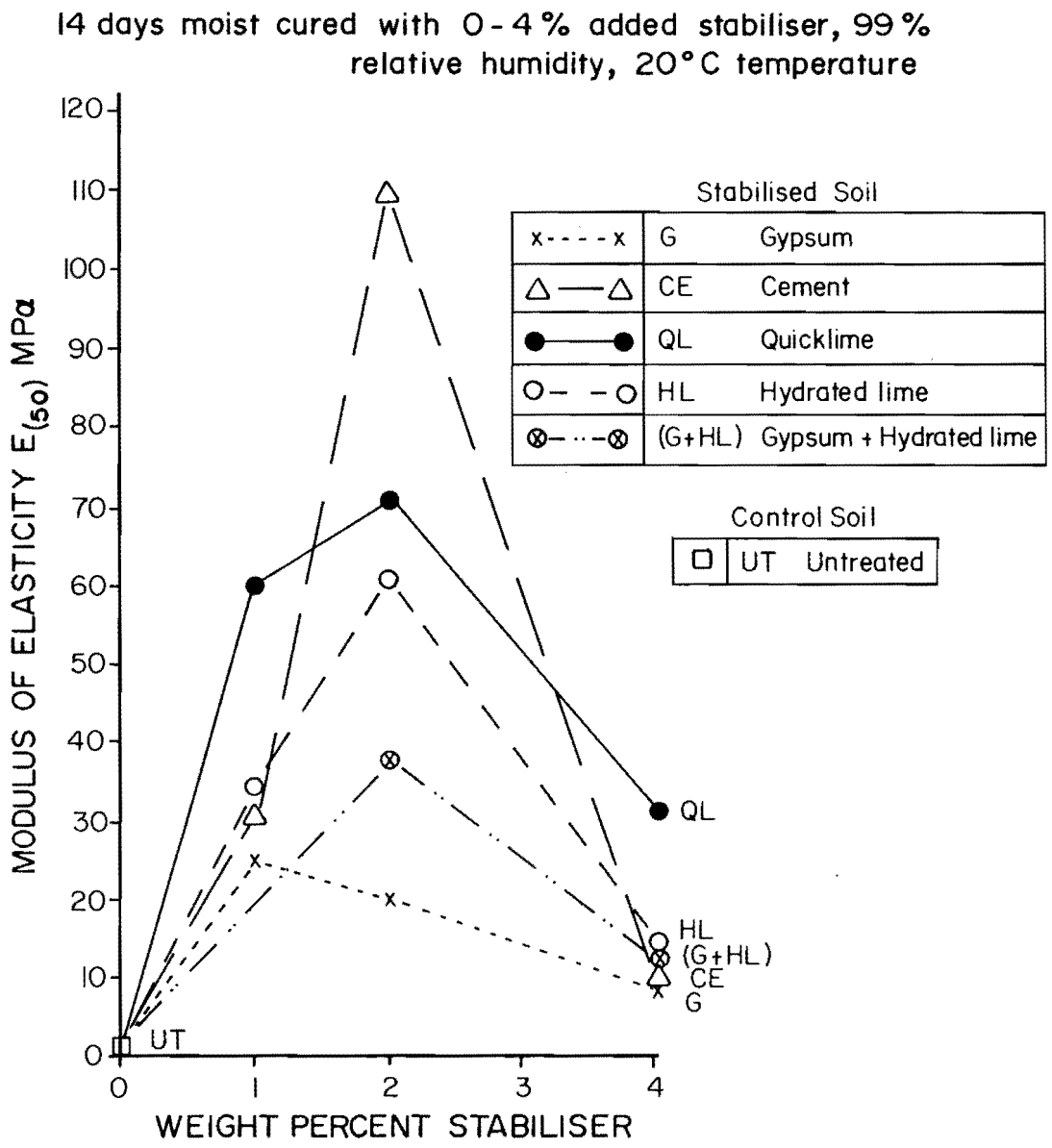


Figure 3·7: Modulus of elasticity ($E_{(50)}$- tangent method) for natural soil and chemically stabilised samples

Finally on the basis of test results it can be concluded that the increase in the modulus of elasticity of lime and cement treated samples is due to the increase in compressive strength and the reduction in strain values of stabilised samples

3.3. Shear Strength

3.3.1. Test Methods and Results

The shear strength parameters (c and ø) for recompacted, untreated and chemically stabilised samples were measured using undrained shear box tests. The untreated and stabilised samples after 14 days moist curing (99% relative humidity and 20° C) were compacted in a single layer at 95% ± 2% of maximum dry density (Appendix 9). Testing was carried out on unconsolidated and partially saturated (11-16%) cylindrical samples (with 6.3 cm diameter and 2.0 cm thickness) in a non-reversing Wykeham Farrance Shear Box. Normal stresses of 43, 74, 106 and 137 kPa were used, and samples were sheared at a constant rate of 1.2 mm per minute.

The cohesion (c) and angle of internal friction (ø) values for untreated and chemically stabilised samples after 14 days moist curing are illustrated in Figs 3.8 and 3.9 respectively and a summary of test data is given in Table 3.3. Fig 3.10 shows the shear strength values for treated and untreated samples on the basis of their angle of internal friction and cohesion at 45 kPa normal stress. This normal stress was chosen according to the thickness of overburden from which the sample was collected (2.3 m).

3.3.2. Untreated Samples

Figures 3.8 and 3.9 indicate that the recompacted untreated loess colluvium sample has a low cohesion (30 kPa) and a high angle of internal friction (39°). The low cohesion value for the recompacted untreated sample is a consequence of its low clay content (14%) and poor cementing between grains, as suggested by SEM analysis (section 4.3.2.2).

The high angle of internal friction for the untreated samples is related to:

a) the well graded nature of the silty soil (Figure A3.1) which results in a large amount of interlocking soil particles during shearing; and

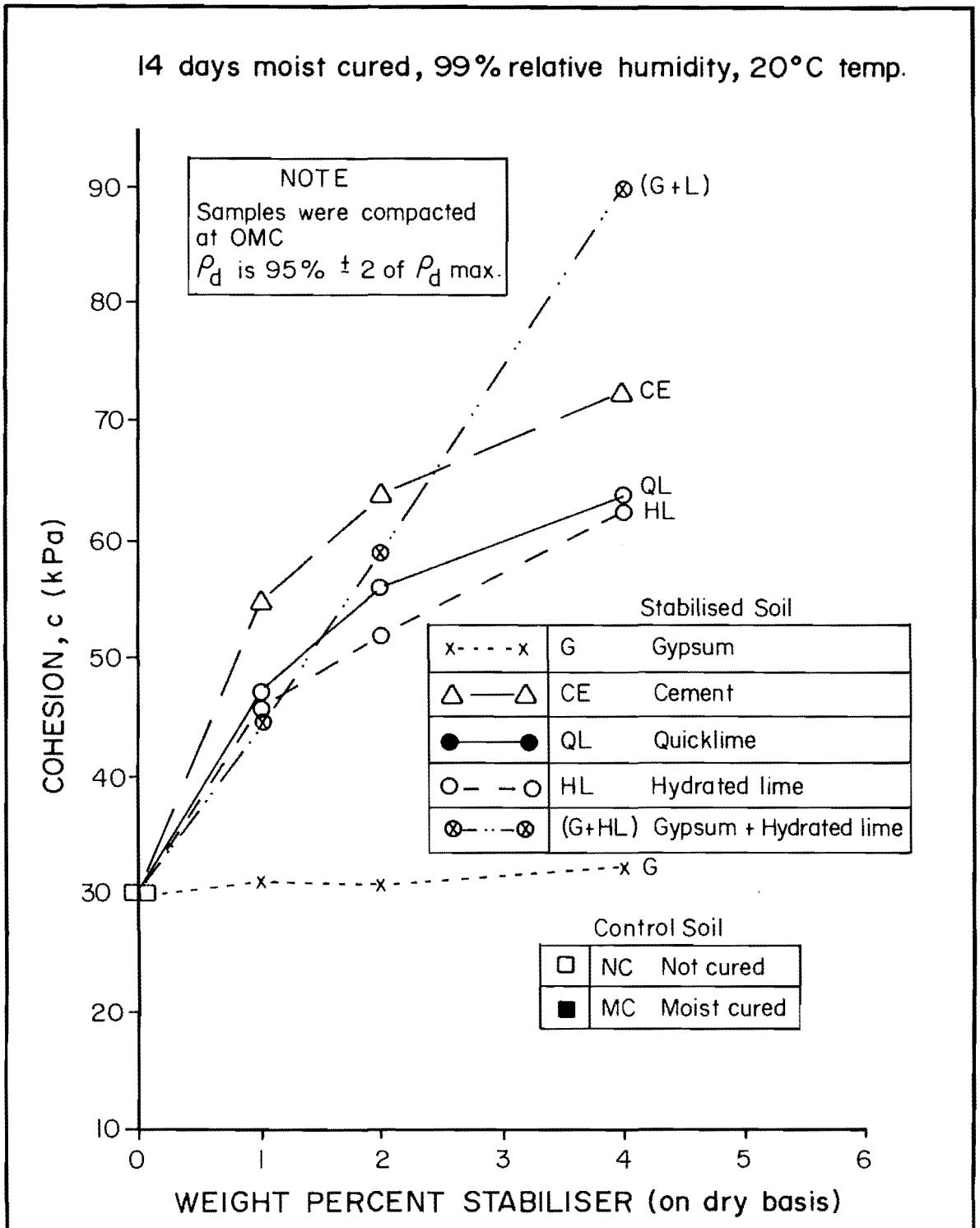


Figure 3·8: Cohesion values for control soil and stabilised soil from undrained shear box tests

b) the dominance of quartz and feldspar minerals in the silt size fraction of the untreated loess-colluvium, as these minerals possess high friction angles (26-30°; Lamb and Whithman, 1979).

3.3.3. Hydrated lime-treated Samples

Figure 3.10 shows that the application of hydrated lime significantly improves the shear strength properties of the stabilised samples. At 1 and 2% addition of hydrated lime, the cohesion value increases by 16 and 22 kPa respectively, relative to the untreated samples. At higher concentrations of stabiliser this trend is continued and the cohesion value of 4% hydrated lime stabilised samples is 2 times that of the untreated samples (63 kPa). The increase in cohesion values of the lime/soil mixtures is due to the formation of crystalline pozzolanic products which cement the soil grains together.

Figure 3.9 shows that the angle of shearing resistance (ø) increases by 3-5° with the application of 1% and 2% of hydrated lime. However, at the 4% hydrated lime addition the friction angle decreases relative to the 1-2% stabilised samples, but still remains greater than for the untreated samples.

The increase in the angle of shearing resistance with the application of 1% and 2% hydrated lime is assumed to be due to changes in particle size distribution of the treated samples (Table 2.2). The reduction in the angle of internal friction at 4% concentration of stabiliser can be related to the presence of unreacted lime "gel" that acts as a lubricant on which the grains can slide relative to each other. The presence of excess gel is suggested by the SEM and XRD results (Section 4.3.3.2). Therefore the increase in strain values, the reduction in the unconfined compressive strength values and the angle of shearing resistance could all be the result of the presence of unreacted lime "gel" at 4% quicklime, cement, and hydrated lime treated samples.

Shear strength values for hydrated lime treated samples were calculated using Coulomb's equation, and are summarised in Table 3.3.

Figure 3.10 combines the values of cohesion and friction angles (Figs 3.8 and 3.9) to produce the shear strength values for untreated and stabilised samples at a normal stress of 45 kPa. The results (Fig 3.10) further indicate that the application of 1% and 2% by weight of hydrated lime increases the shear strength of stabilised samples relative to the untreated sample. This trend is continued at

Table 3.3. Undrained Shear Strength Parameters for Untreated and Treated Samples.

TYPE OF STABILISER	ANGLE OF INTERNAL FRICTION (ø)	COHESION VALUE (kPa)	SHEAR STRENGTH at 45 (kPa) σc
NOT CURED			
0%	30	30	55
MOIST CURED			
0%	39	30	66
GYPSUM			
1%	39	31	67
2%	40	31	69
4%	40	33	70
QUICKLIME			
1%	43	47	90
2%	45	56	101
4%	43	64	106
HYDRATED LIME			
1%	42	46	86
2%	44	52	95
4%	43	63	105
PORTLAND CEMENT			
1%	41	55	94
2%	45	64	109
4%	44	73	117
GYPSUM+HYDRATED LIME (1:1 ratio)			
2%	44	59	99.5
4%	42	90	129.0

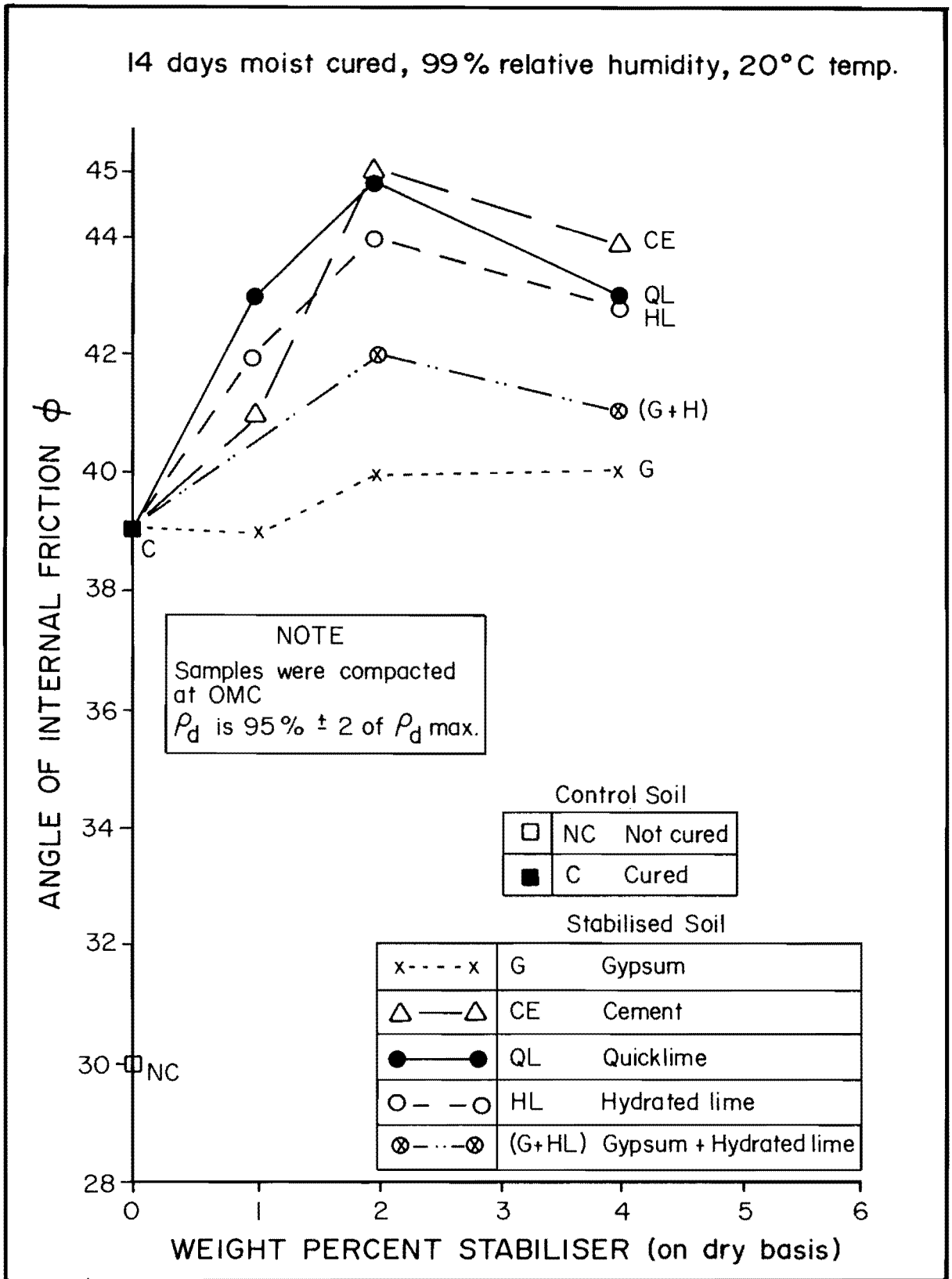


Figure 3·9: Angle of internal friction for the control soil and stabilised soil from undrained shear box tests

higher concentration of stabiliser, so that at 4% addition of hydrated lime the shear strength value is almost two times relative to the shear strength value for untreated soil.

3.3.4 Quicklime-treated Samples

Figure 3.10 shows that quicklime has a similar effect on the c and ø parameters of stabilised soil to that of hydrated lime, although increases in shear strength are greater for quicklime treated samples than for hydrated lime treated samples. For example, the shear strength of 1% and 2% quicklime-treated samples is 90 kPa and 101 kPa respectively, while at the same concentrations, hydrated lime treated samples possess shear strength values of 86 kPa and 95 kPa.

3.3.5. Cement-treated Samples

Figure 3.8 indicates that with the application of 1% and 2% by weight of Portland cement the cohesion values of the soil/cement mixtures significantly increases. At 4% concentration of cement the cohesion value is almost 2.5 times the cohesion values obtained for the untreated samples.

Figure 3.9 shows that the angle of shearing resistance of stabilised loess-colluvium samples increases with the application of 1% by weight of Portland cement. The maximum angle of internal friction is obtained for 2% stabilised samples. However, a slight reduction in the angle of friction (1-2°) can be observed at the 4% concentration of cement treated samples. Finally, Fig 3.10 shows that with 2-4% application of Portland cement and 45 kPa normal stress the shear strength of cement treated samples is two times the shear strength of untreated sample.

3.3.6. Gypsum-treated Samples

The application of gypsum does not significantly change the cohesion and angle of friction of the stabilised samples and the shear strength of gypsum treated samples is similar to that of untreated samples (Fig 3.10 and Table 3.3).

The test results (Table 3.3) indicate that with the application of 2% of mixed stabiliser (gypsum and hydrated lime) the cohesion values of the stabilised samples significantly increases (to two times of the cohesion value of the untreated soil). With application of higher concentrations (4%) of this mixture the cohesion is three times that of the untreated sample.

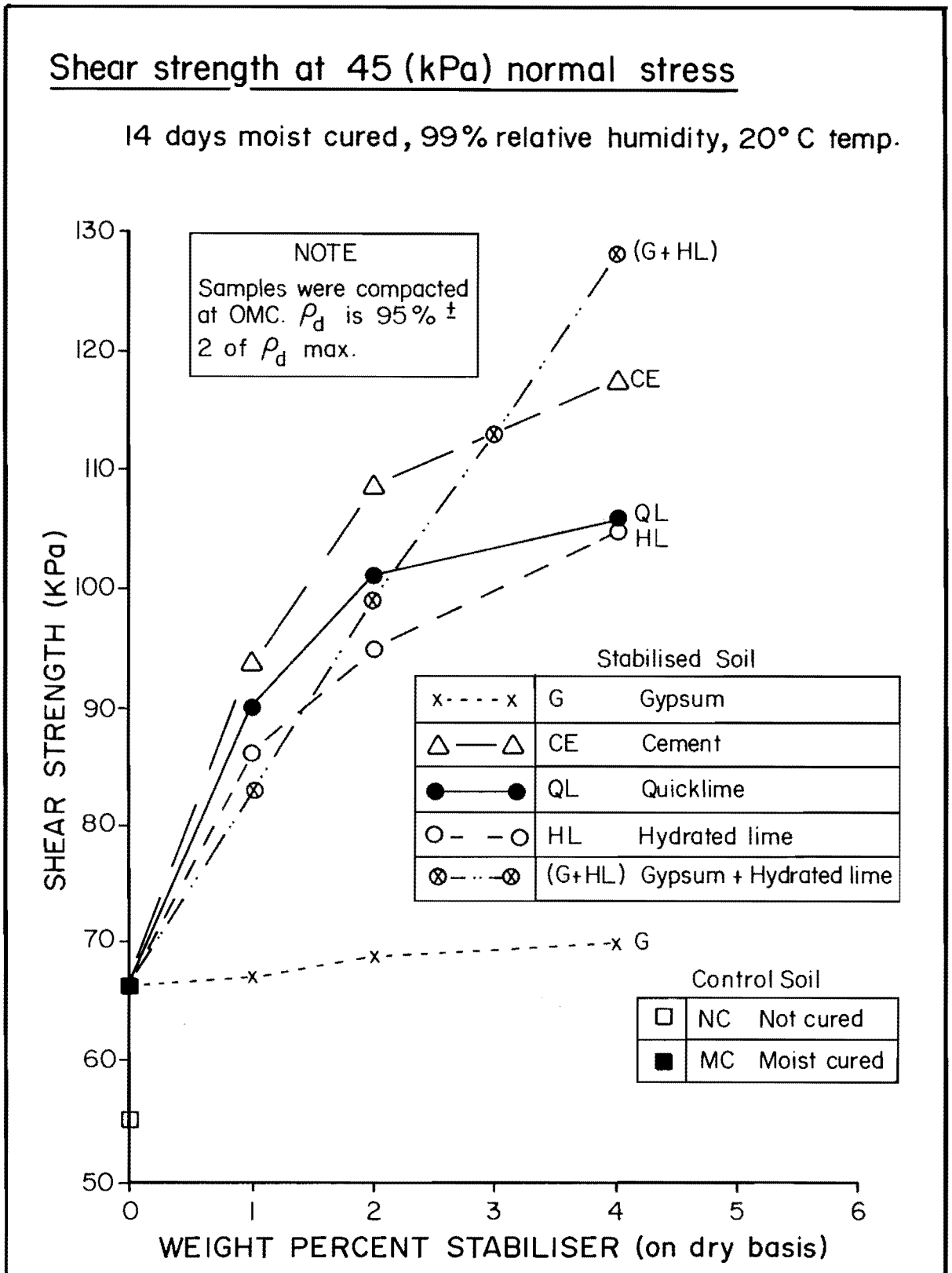


Figure 3·10: Shear strength for the control and stabilised soil

The application of mixed stabiliser produces the highest shear strength value for all stabilised samples tested in this study. These results are in agreement with Trank and Esktrom, (1981) who obtained higher shear strength values with application of a mixture of gypsum and quicklime (1:1 ratio) relative to equal amounts of pure quicklime for stabilisation of soft clay. It seems that very high cohesion values in mixed stabilised samples is due to the crystallisation of ettringite (refer section 4.3.3.2), the needle-like morphology of which produces greater interlocking during shearing. Furthermore Fig 3.9 shows that the angle of friction increases by 3 degrees at 2% application of mixed stabiliser, but reduces by 1-2 degrees at 4% concentration of mixed stabiliser.

3.4. Synthesis

On the basis of test results the following points can be concluded.

1) The application of quicklime, hydrated lime and Portland cement improves the unconfined compressive strength of stabilised loess samples by 2-3 times relative to that of untreated loess samples.

2) Quicklime, hydrated lime and cement treated samples all possess maximum unconfined compressive strength at 2% concentration, while a decrease in unconfined compressive strength is obtained at 4% concentrations for all stabilisers used. However, strength values at the 4% level are still higher than the strength values for untreated samples.

3) At 1% and 4% concentrations, quicklime treated samples possess greater unconfined compressive strength relative to all other stabilised samples at these concentrations, while at 2% concentration of stabiliser, cement treated samples produce the maximum unconfined compressive strength.

4) The application of gypsum does not significantly improve the unconfined compressive strength of stabilised soil.

5) The unconfined compressive strength of mixed stabilised (gypsum and hydrated lime 1:1 ratio) samples is very similar to that obtained for hydrated lime-treated samples, while samples treated with mixed stabiliser possess greater shear strength to that of hydrated lime treated samples.

6) Stabilised samples possess lower dry density but greater unconfined compressive strength relative to untreated samples. The

maximum compressive strength for quicklime, hydrated lime and cement-treated samples at each concentrations of stabiliser correlated with those specimens possessing the greatest dry densities. Furthermore, minimum unconfined compressive strength was correlated with those specimens possessing the lowest dry densities.

7) Application of hydrated lime, quicklime and Portland cement improves the strain deformation properties of the stabilised samples by producing a more brittle material relative to the untreated sample. Also, the maximum compressive strength obtained for all stabilised samples correlates with those samples showing minimum strain deformation.

8) The shear strength of lime and cement treated samples significantly improves relative to the untreated soil. This increase in shear strength is due to an increase in cohesion and the angle of friction of stabilised samples.

9) The increase in angle of shearing resistance is greatest at the 2% level for all stabilised samples. Two percent cement and quicklime treated samples produce the largest increase in friction angle relative to untreated soil from 39° to 45°.

10) With the application of 1-4% stabilisers there is a significant increase in the cohesion values of all stabilised samples, with the exception of gypsum treated samples.

11) The greatest cohesion and shear strength are obtained for samples with mixed stabiliser. This is due to the formation of ettringite in the stabilised samples, whose fibre like crystals interlock during the shearing process.

12) The major effect of hydrated lime, quicklime, Portland cement, and mixed stabiliser application on shear strength is a substantial (16-60 kPa) increase in cohesion values and a minor (3-5°) increase in the angle of internal friction of the stabilised samples relative to the untreated samples.

CHAPTER FOUR: SOIL CHEMISTRY AND MINERALOGY

4.1 INTRODUCTION

This chapter deals with the chemistry and mineralogy of the untreated and stabilised samples. Objectives of Chemical study are:

a) To assess the chemistry of the untreated samples, and to relate chemical properties to the physical behavior of the natural soil (e. g. dispersion/erosion swelling).

b) To determine the changes in chemistry of the stabilised samples resulting from the application of chemical stabilisers, and to relate these changes to their physical and strength properties.

Chemical analyses of treated and untreated samples was carried out using the following techniques:

a) Determination of organic carbon
b) Analysis of soluble salt concentration in pore water
c) Determination of Cation exchange capacity and exchangeable cations
d) X-Ray fluorescence analyses (XRF)
e) Determination of $_{p}H$

In addition, the chemical composition and grainsize distribution of each chemical stabiliser were determined using X-Ray fluorescence and dry sieve analysis. This provides information about their different reactivity with the loess-colluvium soil. Furthermore, $_{p}H$ tests on chemically stabilised samples were carried out to assess the effect of chemical stabilisers on soil $_{p}H$ and to relate these results to the reactivity between the stabilising agents and soil minerals.

X-Ray diffraction (XRD), Scanning Electron Microscopy (SEM), and Energy Dispersive X-Ray Analysis (EDAX) were used; a) to study fabric and mineralogy of the untreated sample to provide a basis for comparison of mineralogical and textural changes that can be observed in the treated samples, and b) to relate the fabric and mineralogical properties of untreated and treated samples to their respective physical properties.

4.2.Soil Chemistry

4.2.1.Test Methods and Results

The Organic carbon concentration in the P-layer of Whaka Terrace loess was measured using the technique of Walkley and Black (1934). The test procedure is out lined in Appendix 10 and test results

4.2.2. Organic Carbon Content

Edward and Bremner (1976) have suggested that there is a close relationship between concentration of organic carbon content (eg. plant rootlets) and the stability of soil aggregates immersed in water. The presence of a high level of organic carbon binds the clay particles and prevents their disaggregation in water. Laffan (1973) has indicated that dispersive soils characteristically have an organic carbon content less than 0.5% of their soil mass.

As the bulk sample was taken from P layer it has an extremely low organic carbon content, equivalent to only 0.3% by weight of the soil mass (Table 4.1). The extremely low concentration of organic carbon in the Whaka Terrace loess-colluvium soil can possibly be regarded as a factor contributing to the dispersive behaviour of the soil.

4.2.3. Soluble Salts Concentration

The test results (Table 4.1) indicate that the concentration of total soluble salts, ($MgSO_4$, $CaSO_4$, NaCl) in the pore water of the untreated bulk sample is very low (0.36%). The analyses of water-soluble cations and anions indicate that sodium chloride is the dominant salt, while calcium and magnesium sulfate are present only in very small quantities.

The low concentration of soluble salt (0.36%) in the Whaka Terrace bulk sample is regarded as a factor contributing to the dispersiveness of the loess soil sample, while high concentration of soluble salt produces a net attractive force between clay particles, promoting their flocculation (Rallings, 1966). Furthermore, high percentage of exchangeable sodium cations in the pore water of the bulk sample (8.5) reduces soil aggregation and contributes to soil dispersion. This is due to the presence of the highly hygroscopic univalent sodium, forming an intensely hydrated sodium-clay system , as a result of which the sodium-clay system has a strong tendency to disperse in a aqueous solutions. The calcium is divalent and has a lower capacity to hydrate, allowing greater aggregation of the clay minerals (Martin and Richards, 1959 ; Rowell et al, 1969). This is supported by plotting the results of E.S.P and soluble salt concentration on Fig 4.1.

Table 4.1 Chemical and Mineralogical properties of Loess-colluvium from Whaka Terrace (Port Hills).

PARAMETER	UNIT	MEAN VALUE			
ORGANIC CARBON CONTENT	%	0.3			
pH	-	7.6			
TOTAL SOLUBLE SALT	me/l	0.36			
EXCHANGEABLE CATIONS		Ca^{2+}	Na^{+}	Mg^{2+}	
IN PORE WATER	me.% *	0.14	2.60	0.1	
CATION EXCHANGE CAPACITY	me.%	7.3			
EXCHANGEABLE		Ca^{2+}	Na^{+}	Mg^{2+}	K^{+}
CATIONS	me.%	3.51	0.66	2.66	0.08
TOTAL EXCHANGEABLE BASES (TEB)	me.%	6.91			
EXCHANGEABLE SODIUM PERCENTAGES (E.S.P)	-	8.50			
SODIUM ADSORPTION RATIO (S.A.R)	-	7.5			
CLAY MINERALS ILLITE	%	50			
ILLITE-CHLORITE	%	20			
CHLORITE	%	20			
± 10% KAOLINITE	%	<10			

* milli equivalent per 100 g of soil.

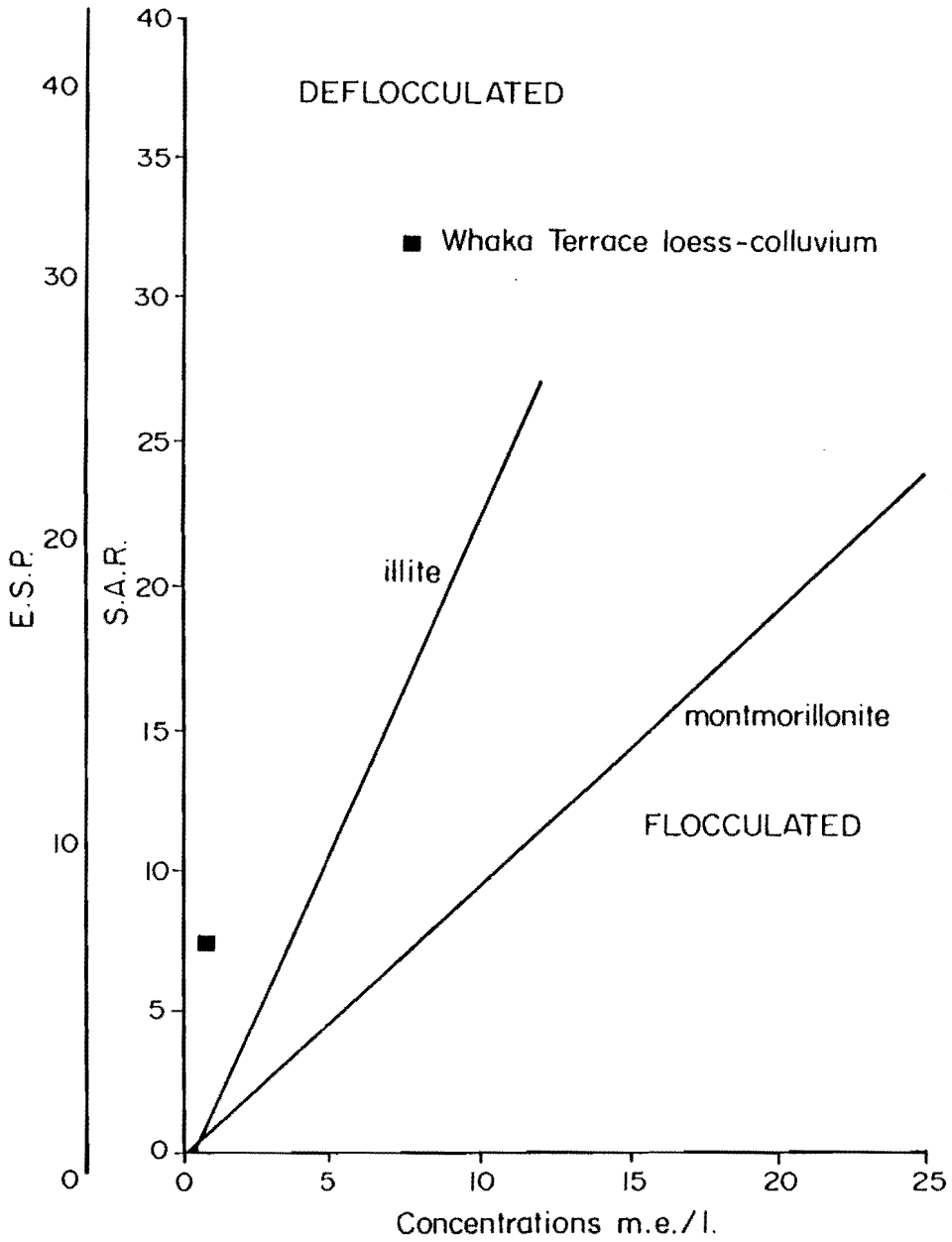


Fig. 4.1 Relationship between S.A.R and soluble salt concentration in pore water for Whaka Terrace loess-colluvium (based on Rallings, 1966).

are given in Table 4.1.

Soluble salt concentration and the type of exchangeable cations in pore water of a 1:5 soil water extract were measured using the electrical conductivity method of Metson (1961). The test procedure is outlined in Appendix 10 and the test results are summarised in Table 4.1. The sodium adsorption ratio (S.A.R) from exchangeable cations values for the untreated sample was calculated according to the following formula from Richards (1954):

$$S.A.R. = Na^{+} / \sqrt{1/2(Ca^{2+} + Mg^{2+})}$$

where, Na^{+}, Ca^{2+} and Mg^{2+} are the concentration of cations in the pore water as milli equivalent per litre (Me/l). Furthermore, exchangeable sodium percentage (E.S.P.) of the untreated sample was calculated using following formula from Richards (1954).

$$E.S.P. = 100(-0.0126+0.01425\ S.A.R)/\ 1+(-0.0126+0.01475\ S.A.R.)$$

Cation exchange capacity for the Whaka Terrace Loess-colluvium bulk sample was determined by preparing a leachate sample of the soil. The leachate was subsequently analysed using atomic absorption (AA) techniques according to procedure of Blakemore et al (1977). The test procedure is outlined in Appendix 10 and the test data is given in Table 4.1. The effect of chemical stabilisers on cation exchange capacity and exchangeable bases of loess-colluvium soil after 14 days moist curing were also studied using the same techniques as outlined for the untreated sample. The results are summarised in Table 4.2.

X-Ray Fluorescence (XRF) analyses were carried out on untreated Whaka Terrace loess-colluvium, and on the chemical stabiliser agents, using a Phillips PW 1400 automatic spectrometer. Analyses were carried out with a Cr tube operating at 50 kV and 50 mA. Iterative mass absorption corrections were performed using an online HP 9835B computer following the method of Norish and Hutton (1969). The test procedure is outlined in Appendix 10, and the results are given in Tables 4.3 and 4.4.

$_{p}H$ tests on soil suspensions of untreated and treated samples were carried out using the Electrometric Method given in New Zealand Standard 4402 (1980) part 1 test 12 (A) page 75-76. The test result is given in Table 4.2.

4.2.4. Cation Exchange Capacity

The cation exchange capacity of a soil is measure of the net negative charge of the clay and expressed in me.% .

The test result (Table 4.1) indicates that cation exchange capacity of Whaka Terrace loess-colluvium soil is low (7.3 Me.%), as would be expected for an illitic soil. Table 4.1 further indicates that the level of exchangeable calcium cations is low (3.51 me.%) while the concentration of exchangeable sodium cations is high (0.66 me.%). In addition, the data indicates that the concentration of exchangeable magnesium cations and potassium are low to very low respectively (2.66 me.% for Mg^{2+} cations and 0.08 me.% for K^{+} cations). It seems that the very low concentration of K^{+} exchangeable cations is due to fixation of K^{+} in the tight structure of illite.

The following points about the effect of chemical stabilisers on the C.E.C and exchangeable cations of stabilised samples can be concluded;

1) The data (Table 4.2) indicates that the C.E.C of stabilised samples is relatively higher than the C.E.C of untreated sample (eg. C.E.C. of 4% hydrated lime treated sample is 9.78 me.% while, C.E.C. of untreated sample is 7.30 me.%).

2) The application of quicklime produces the most pronounced increase in cation exchange capacity (Table 4.2), while gypsum has the least effect on cation exchange capacity (eg. C.E.C of 4% quicklime-treated sample is 10.16 me.% while, C.E.C. of 4% gypsum-treated sample is 6.95 me.%).

3) The concentration of exchangeable K+ cations significantly increases with the application of hydrated lime and quicklime, (table 4.2) being greatest for 4% quicklime stabilised sample.

The increase in exchangeable cations results from the decomposition of the illite lattice due to the attack of lime on the illite structure. This argument is supported by the fact that K^{+} is not available from the chemical composition of the added stabilisers (Table 4.3.).

The lack of increase in the concentration of K^{+} cations in the gypsum treated samples further confirms the low reactivity between gypsum and clay minerals in the stabilised samples.

Table 4.2 Effect of chemical stabilisers on the cation exchange capacity and $_pH$ of Whaka Terrace loess.

TYPE OF STABILISER	CATION EXCHANGE CAPACITY (me.%)	EXCHANGEABLE BASES (me.%)				$_pH$
		Ca^{2+}	Na^{+}	Mg^{2+}	K^{+}	
MOIST CURED						
0.0%	7.30	3.51	0.66	2.66	0.08	7.6
GYPSUM						
1%	7.1	-	0.78	2.65	0.11	7.6
4%	6.95	-	0.86	2.49	0.14	7.6
QUICKLIME						
1%	8.72	-	0.94	2.15	0.14	12.4
4%	10.16	-	1.02	2.88	0.27	12.6
CEMENT						
2%		-	-	-	-	12.0
4%		-	-	-	-	12.1
HYDRATED LIME						
1%	7.97	-	0.9	-	0.11	12.1
4%	9.78	-	1.1	3.07	0.22	12.6

Table 4.3 Chemical composition of stabiliser agents.

ELEMENTS	UNIT	CEMENT	QUICKLIME	HYDRATED LIME	GYPSUM
SiO_2	%	21.33	0.84	0.59	7.55
TiO_2	%	0.25	0.05	0.04	0.08
Al_2O_3	%	4.22	0.28	0.2	1.54
Fe_2O_3	%	2.27	0.38	0.28	0.57
MnO	%	0.29	0.02	<0.01	<0.01
MgO	%	0.99	1.2	0.99	0.71
CaO	%	66.79	81.09	68.5	38.09
Na_2O	%	0.28	0.42	0.22	0.53
K_2O	%	0.24	0.03	0.03	0.26
P_2O_5	%	0.13	0.08	0.07	0.16
LOI	%	2.0	14.68	28.76	15.35
total	%	99.83	99.06	99.68	64.84

4.2.5. X-Ray Fluorescence (XRF) Analysis

XRF analyses indicate that silica and alumina are the dominant elements present in the untreated loess-colluvium samples (Table 4.4). The chemical composition and size fraction of each stabiliser (Table 4.3 and 4.5.) indicates that hydrated lime is a fine grained type (43% of its grains are finer than 0.0625mm) with a CaO content of 68.5% . Quicklime is a coarse grained type (60% remains on 1 mm sieve) with a CaO content of 81.0 %. Both hydrated lime and quicklime contain less than 1% alumina and silica (as Al_2O_3; SiO_2). Portland cement composition indicates the presence of 21% SiO_2; 4% Al_2O_3 and 67% CaO (Table 4.3.). Gypsum is fine grained (96% finer than 0.125 mm) and consists of 7% SiO_2 and 38% CaO.

Analysis of the chemical composition of the stabilisers provides insight into their different reactivity with the loess-colluvium soil sample. The percentage of CaO available for reaction with the clay minerals is greatest in quicklime and lowest in gypsum, so that for a given concentration and curing time there is a greater potential for pozzolanic reaction to take place in quicklime-treated samples. The high availability of SiO_2 and Al_2O_3 in Portland cement results in production of different types of pozzolanic products relative to those in lime treated samples, and these are discussed in section (4.3.3.2).

4.2.6. Soil $_pH$

Research has illustrated that soil dispersivity increases with increasing $_pH$, and that soils with dispersive properties generally exceed $_pH$=4.5 (Rallings, 1966; Decker et al, 1977; and Laffan, 1973). Tunnel gullying has been observed to occur mainly in soils with a $_pH$ between 7 and 9 (Ingles and Aitchison, 1969).

Test results indicate that the untreated loess-colluvium sample from Whaka Terrace is slightly alkaline, with a $_pH$ = 7.6. The $_pH$ value obtained for Whaka Terrace loess is therefore considered to be a factor contributing to soil dispersiveness.

Cementing agents in stabilised soil are formed by hydrated calcium silica, and alumina. These are derived from the dissolution of available alumina and silica in the soil (clay minerals, quartz and feldspar grains) under conditions of high $_pH$. Fig 4.2 illustrates the relationship between the solubility of silica and $_pH$, and indicates that SiO_2 dissolves in alkaline solution when the $_pH$ value exceeds 10.5

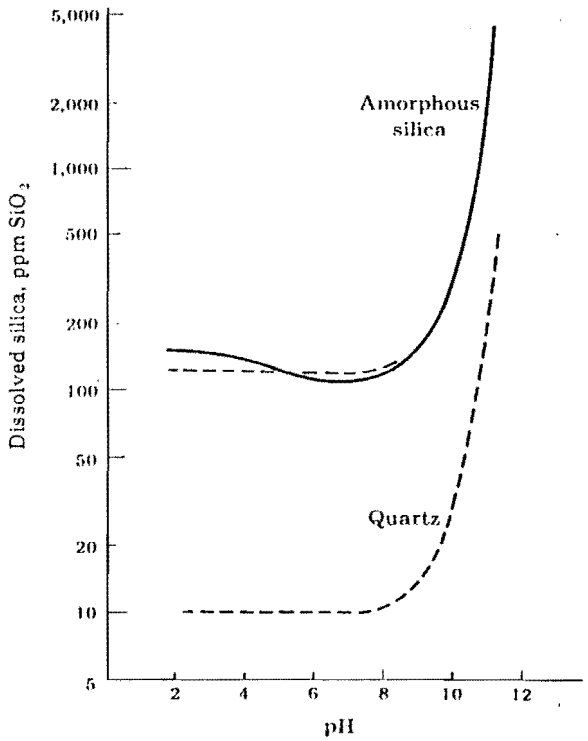


Fig 4.2 Relationship between soil ₚH and solubility of silica at 25° C (from Krauskopf,1967).

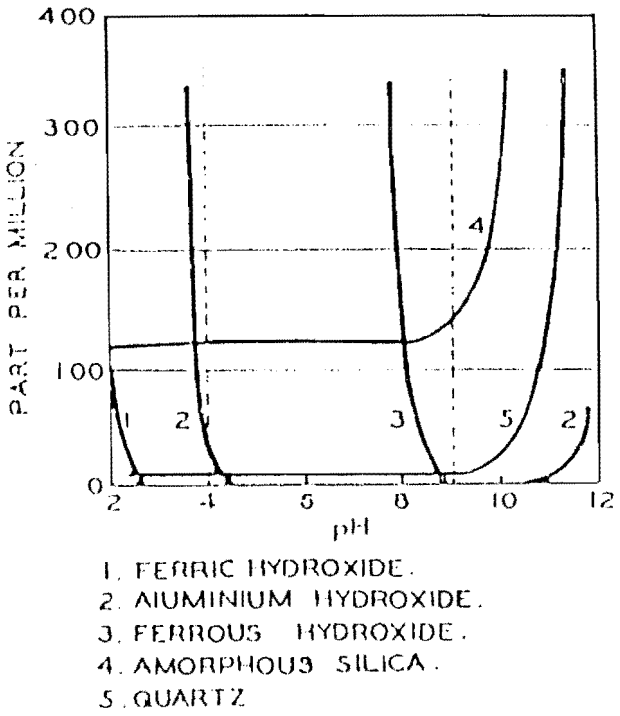


Fig 4.3 Relationship between solubility of hydroxides, quartz and soil ₚH at 20° C (from pickering, 1962).

Table 4.4 Major element analysis in Whaka Terrace loess-colluvium.

ELEMENTS	UNIT	VALUE
SiO_2	%	72.23
TiO_2	%	0.57
Al_2O_3	%	13.41
Fe_2O_3	%	3.25
MnO	%	0.3
MgO	%	1.03
CaO	%	1.43
Na_2O	%	3.32
K_2O	%	2.36
P_2O_5	%	0.11
LOI	%	2.03
TOTAL	%	99.83

Table 4.5 Grainsize analyses of chemical stabiliser agents.

PERCENTAGE OF FINER		STABILISER			
SIZE FRACTION		CEMENT	QUICKLIME	HYDRATED LIME	GYPSUM
mesh	mm				
18	1.0	100.0	40.7	97.8	100.0
35	0.5	99.9	26.3	87.8	99.8
60	0.25	99.8	20.1	72.8	98.8
120	0.125	99.7	16.1	57.5	96.0
230	0.0625	92.8	5.4	43.0	22.3

(Krauskopf, 1967). Furthermore, Fig 4.3 shows that aluminium hydroxide which is an amphoteric electrolyte redissolves at an alkali $_pH$ of 10.9 to form soluble aluminates. So that, these soluble silica and alumina with Ca derived from application of chemical stabilisers provides suitable condition for formation of cementing agents (pozzolanic products).

The data in Table 4.2 indicates that the $_pH$ of loess soil increases significantly with application of 1% by weight of hydrated lime and quicklime (after 14 days moist curing) from 7.6 (for natural soil) to 12.1 and 12.4 respectively. With the application of 4% quicklime and hydrated lime the $_pH$ value can be seen to increase slightly to a maximum of 12.6 . From this it can be concluded that the application of hydrated lime and quicklime to loess-colluvium soil provides a suitable environment for the dissolution of silica and alumina for quartz, clay minerals and other sources of silica and alumina, leading to the formation of cementing agents or pozzolanic products.

Application of 2-4% Portland cement increases soil $_pH$ from 7.6 to 12.1, suggesting it has a similar effect to lime application. However, gypsum application was found to have no effect on soil $_pH$, the lack of increase in the $_pH$ value of gypsum treated samples being the principal reason for the absence of pozzolanic products in these samples.

The presence of cementing agents in lime and cement stabilised samples, and the absence of cementing agent in gypsum treated samples, have been supported by (XRD) and (SEM) studies of the stabilised samples (refer to sections 4.3.3.1 and 4.3.3.2). In conclusion, the following points can be stated;

a) $_pH$ can be used as in indicator to assess the potential of pozzolanic reaction between chemical stabiliser agents (eg. gypsum and Portland cement) and Port Hills Loess, b) $_pH$ can be considered as a criteria to assess the reactivity of varying concentrations of soil/lime and soil/cement mixtures.

4.3. Soil mineralogy

4.3.1. Tests Methods And Results

XRD analyses were carried out at the Department of Geology, University of Canterbury. Tests were run using a Philips PW 1050 X-ray

diffractometer, with nickel-filtered Cu kα radiation. The tube was run at 34 kV and 34 mA with the divergence slit set at 1°. Samples were scanned from 2° 2 θ to 42° 2 θ at a speed of 1° of 2 θ/minute.

The clay mineral species were identified by their characteristic x-ray diffraction patterns in conjunction with different types of treatment, namely glycolation, heat treatment and HCl treatment. The treatment procedure and a summary of the effect of various treatment techniques on clay mineral species is given in Appendix 11. The XRD analysis on the clay fraction of untreated sample is shown in Fig 4.4.

The relative abundances of clay mineral species was determined on the < 2 μm fraction, and oriented samples were prepared using the method of Campbell (1975). The relative abundances were determined using peak height techniques, and the height of specific peaks above the base line on the XRD diffractogram of untreated sample were measured following the method of Hume and Nelson (1982). The calculation procedure is given in Appendix 11, and the results of this study are semi quantitative, with an accuracy of within ± 10% of the true value.

Identification of non clay minerals was carried out on a powder sample of the <45 μm fraction of the soil. Samples were prepared according to Hutchinson (1974), the test procedure is outlined in Appendix 11, and the results are shown in Fig 4.5. The peak height of individual minerals above the base line on the diffractogram of an unoriented powder sample was measured. The results were then compared to the standards of Nelson and Cochrane (1970) to determine the relative abundance of minerals present in the untreated samples. The calculation procedure is outlined in Appendix 11 and the results are summarised in Table 4.7.

XRD analyses on clay fraction (< 2 μm) and bulk fractions of treated samples were prepared using the same techniques as outlined for the preparation of the untreated sample. The diffractograms of treated samples is shown in Fig 4.6.

The structure and morphology of minerals present in the untreated sample and chemically stabilised samples were studied using a Cambridge Stereo Scan 250 (Mk2), and the elemental analysis of specified minerals by a Philips EDAX Pv 9100. Research was carried out at the Botany Department, University of Canterbury. Both clay fraction and bulk fraction were studied, sample preparation is outlined in

Table 4.6 Relative abundances of clay minerals in the clay fraction of Whaka Terrace loess-colluvium.

TYPE OF CLAY MINERALS	PERCENTAGE OF CONCENTRATION ± 10%
MICA (ILLITE)	50%
CHLORITE	20%
ILLITE-CHLORITE MIXED LAYER	20%
KAOLINITE	<5%
UNDIFFERENTIATED	<5%

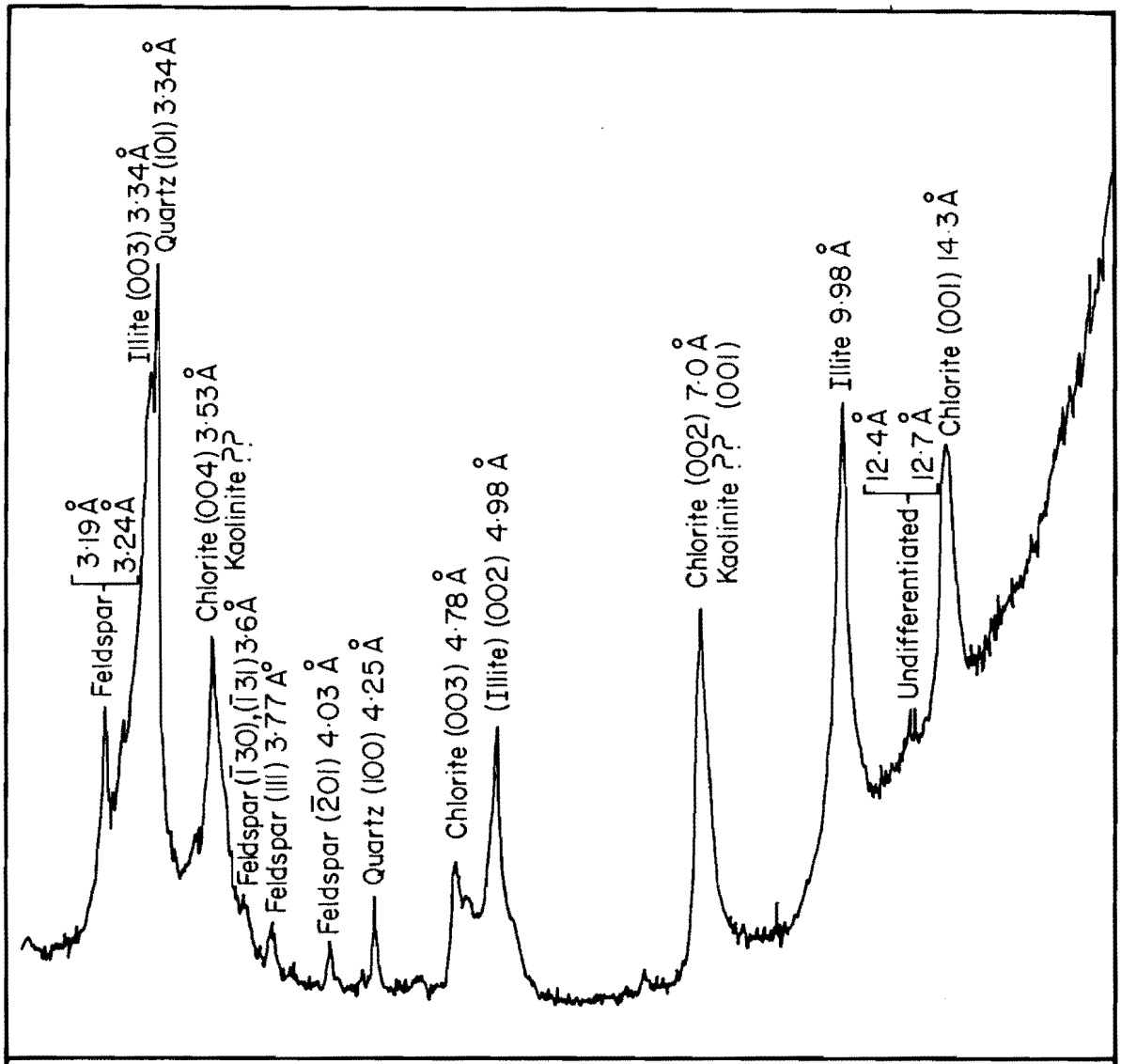


Figure 4.4 Diffractogram pattern of an oriented mount of clay fraction from untreated Whaka Terrace loess - colluvium.

Appendix 11, and the results of SEM observation are shown in Fig 7 to 4.24.

4.3.2. Untreated Samples

4.3.2.1. XRD and SEM Analyses of Clay Fraction

The XRD analyses on mounts of the clay fractions of untreated samples (Fig 4.4) indicate the presence of illite as the dominant clay mineral (50%), kaolinite, Fe-chlorite, illite-chlorite mixed layers, as well as non-clay minerals such as quartz and feldspar. The high proportion of illite in the clay fraction of the loess soil can be related to soil properties such as low activity (0.7) and low plasticity (7).

The SEM analyses of the clay fraction of untreated samples (Fig 4.5) indicates the presence of illite as thin irregular flakes without distinctive shapes and generally <1 μm in size, and the chlorite species are identified by a rosette pattern in plan view.

SEM and XRD analyses of the clay fraction indicate an absence of smectite clays. The absence of smectite clay is probably related to soil alkalinity ($_{p}H$ = 7.6), which makes it unsuitable for the development of smectite (Malcolm et al 1969). The presence of smectite in the P-layer of loess-colluvium at Port Hills (Westmorland subdivision) has been suggested by Glassey (1986), based on a shift of the 13 Å peak to 17 Å after glycolation. However, the results of this study suggest that the 13 Å peak more probably represents swelling chlorite. This is also suggested by the studies of Miller (1971) and Laffan (1977), who do not indicate the presence of smectite in slightly alkaline P-layer samples of Port Hills loess.

4.3.2.2. XRD and SEM Analyses of Bulk Fraction

XRD analysis on the diffractogram of the bulk fraction (powder sample) in Fig 4.6 indicates the presence of quartz, alkali feldspar, plagioclase, analcite and crystobalite. Table 4.7 indicates that quartz and feldspar are the dominant minerals in the Whaka Terrace loess-colluvium bulk sample (40 and 25% respectively).

SEM analyses of the bulk fraction indicate that the untreated sample consists mainly of quartz and feldspar of almost uniform size, with a range of 20-60 μm (Fig 4.7). The void spaces are irregular, and are distributed as a series of small (10-15 μm) cavities through the

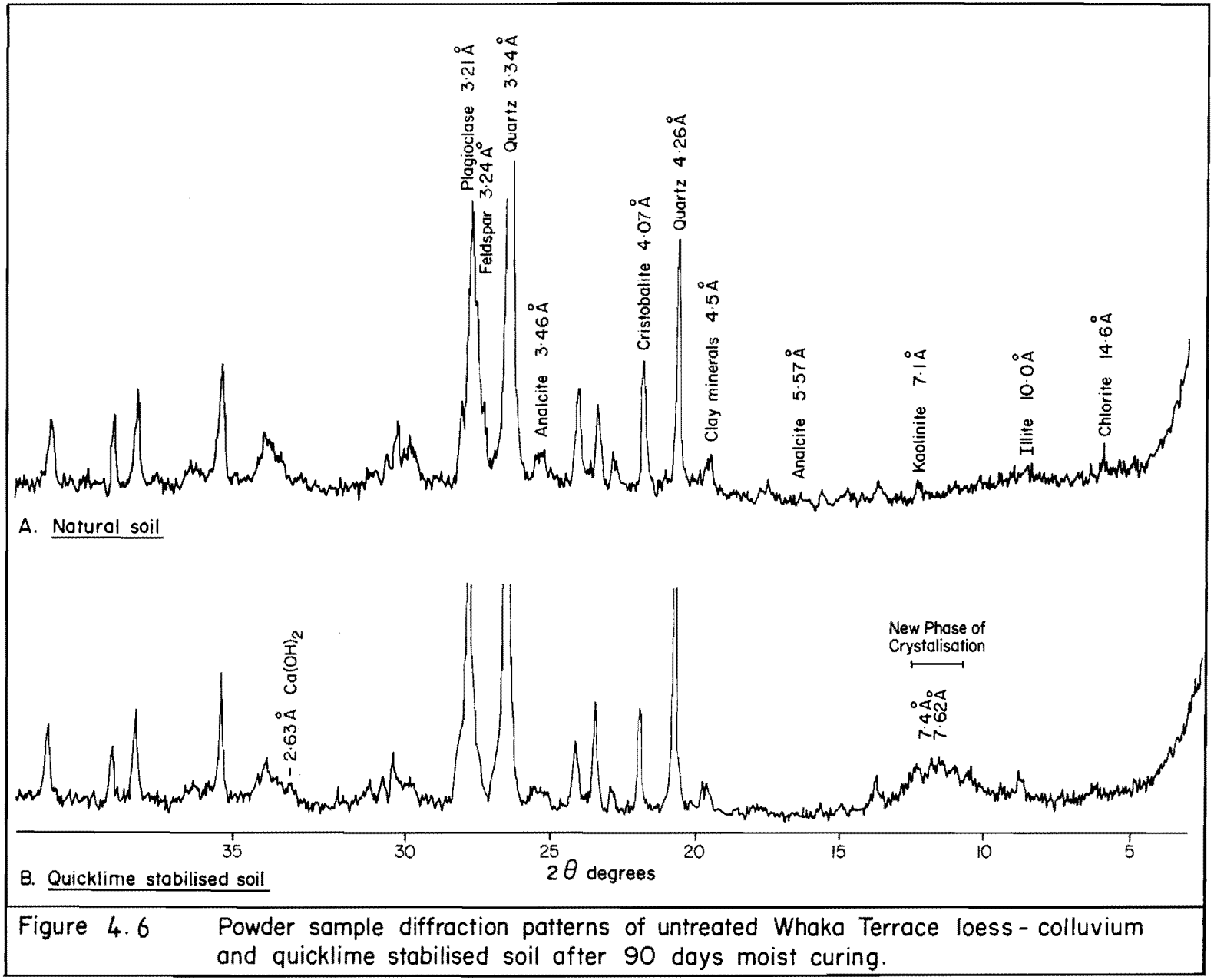


Figure 4.6 Powder sample diffraction patterns of untreated Whaka Terrace loess - colluvium and quicklime stabilised soil after 90 days moist curing.

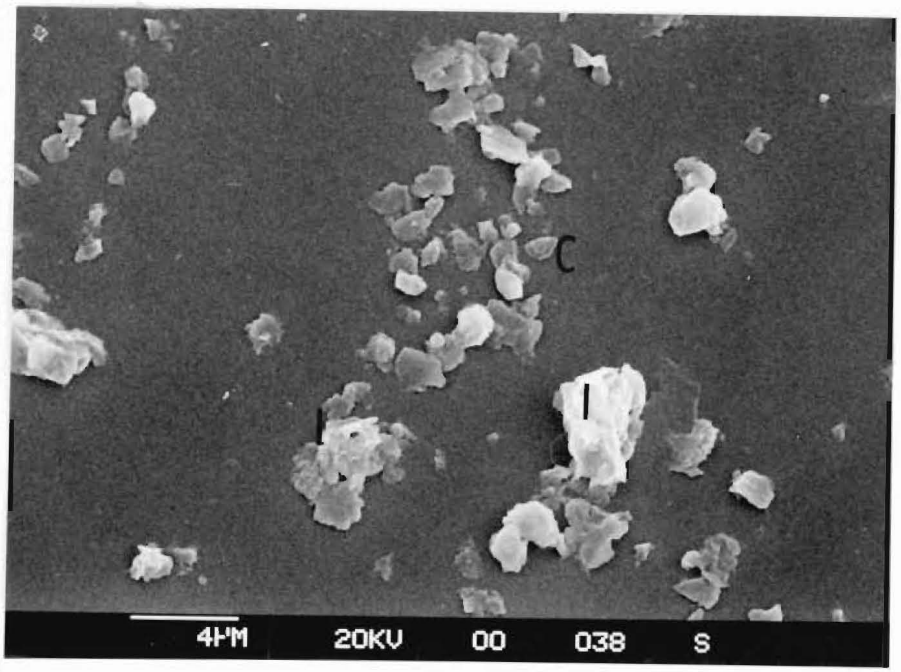


Fig 4.5 SEM micrograph of clay mineral suspension showing chlorite (C) with rosette pattern and illite (I) as thin flaky crystals.

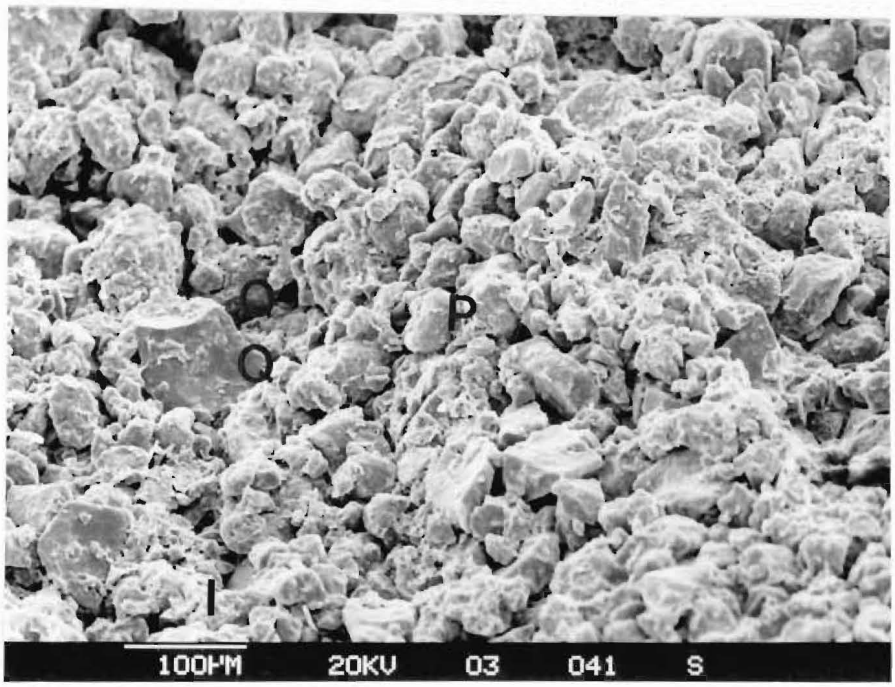


Fig 4.7 Distribution of silt size quartz and feldspar in Whaka Terrace loess, with clay minerals present as thin flaky minerals (I).

Table 4.7 Relative abundances of quartz and feldspar in Whaka Terrace loess-colluvium.

Type OF MINERAL	CONCENTRATION (%)
4.26 Å QUARTZ	13%
3.34 Å QUARTZ	27%
3.25 Å POTASH FELDSPAR	5%
3.2 Å PLAGIOCLASE	20%

material. The clay minerals appear mainly as thin flakes between 1-2 um in size infilling the spaces between the coarser quartz and feldspar grains (Fig 4.8). Quartz and feldspar were distinguished mainly by their morphology and chemical composition, while the clay minerals were identified from their size and morphology. Quartz grain size is in the range of coarse to fine silt (20-40 μm), and grains have a conchoidal surface (Fig 4.8). Plagioclase is in the range of medium to fine silt (10-30 μm), and grains possess a tabular shape and cleavage (Fig 4.9). The presence of plagioclase is also indicated by XRD and EDAX analysis. The elemental analysis of the grain in Fig 4.9 is presented in Table (4.8) and indicates to plagioclase composition (ratio of silica to alumina of 3:1, and a ratio of calcium to potassium of 2:1). Furthermore, Fig 4.8 shows that illite as thin irregular flakes and chlorite species as spikes arranged in a fan shape from side view .

Fabric studies of untreated bulk samples by SEM indicate the presence of small pore sizes(10-15 μm). This can be related to the low permeability ($k=2.6 \times 10^{-8}$ m/s) observed from falling head tests, as well as to the slaking properties observed in the Jar Slake Test, because small pore sizes result in high air pressure and high potential for slaking. Furthermore, SEM study indicates a lack of extensive cementing material (Fig 4.8), which contributes to the erodibility of the untreated samples.

4.3.3. Treated Samples

Pozzolanic reactions are considered to be the source of changes in the mineralogy and fabric of stabilised samples. The reaction occurs when the calcium ions (derived from lime or cement) react with the dissolved silica and alumina (derived from clay minerals, feldspar, quartz at high $_{p}H$ of stabilised soil). Following equations give a simplified explanation of the chemical reactions occurring between lime and soil particles.

$$Ca(OH)_2 \text{----} > Ca^{2+} + 2\ (OH)^-$$

$$Ca^{2+} + 2\ (OH)^- + SiO_2 \text{ (clay mineral or other source) ---}>CHS$$

$$Ca^{2+} + 2\ (OH)^- + Al_2O_3 \text{(clay mineral or other source) --}>CHA$$

where C=CaO, S= SiO_2, A=Al_2O_3 and H=H_2O

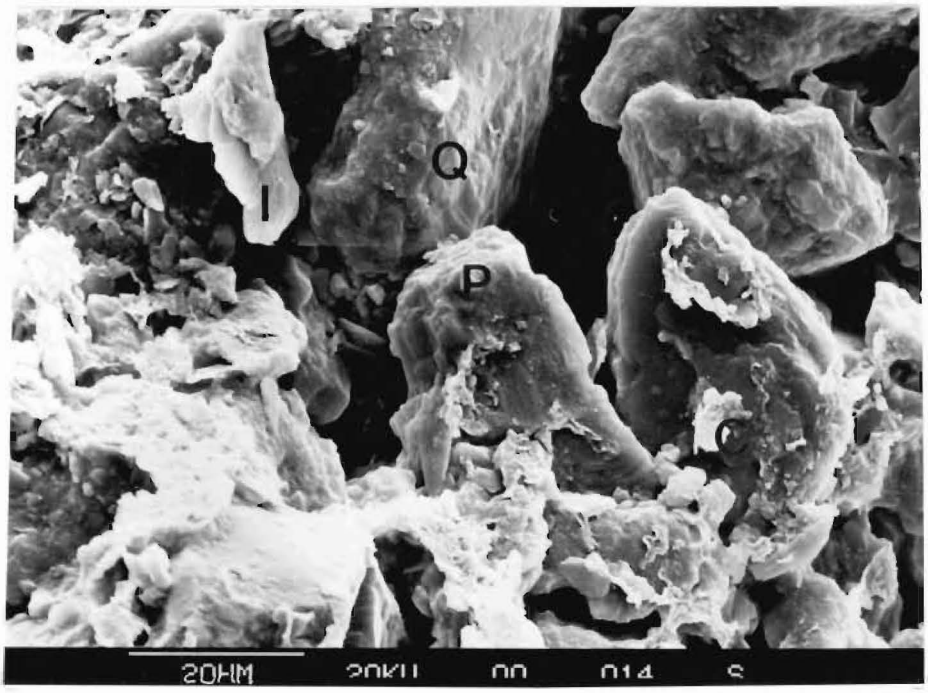


Fig 4.8 Size and morphology of quartz (Q) and plagioclase (P), chlorite (C) and illite (I) (x 1,200).

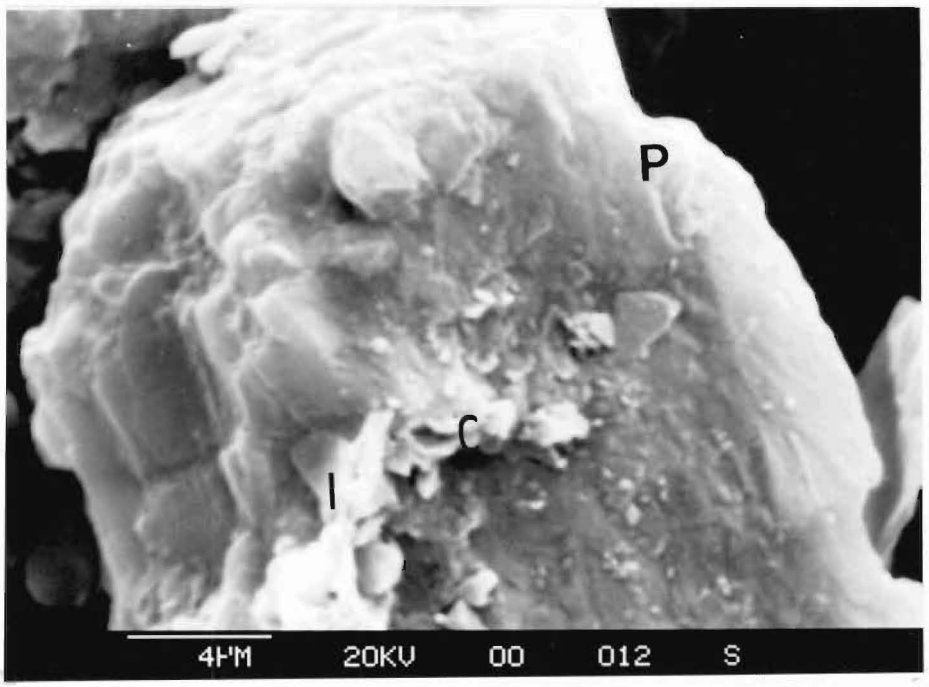


Fig 4.9 High (x 3,500) magnification of plagioclase crystal, (also note the presence of illite (I) and chlorite (C).

Table 4.8. Elemental distribution in a plagioclase from SEM micrograph in Fig 4.9

ELEMENT	WEIGHT PERCENT
Na	1.34
Al	15.54
Si	57.72
P	5.83
S	4.22
K	1.04
Ca	2.88

Table 4.9 Elemental distribution of pozzolanic products from SEM micrograph of cement-treated sample in Fig 4.14.

ELEMENT	WEIGHT PERCENT
Al	12.56
Si	50.10
Ca	11.01
S	3.03
K	3.82
P	4.26
Ti	0.89
Na	0.62
Mg	0.83

4.3.3.1 XRD Analyses

i) Clay Fraction

XRD analyses on oriented mounts of the clay fraction of chemically stabilised sample after 14 days moist curing were carried out to determine the effect of chemical stabilisers on clay mineralogy as well as to detect the presence of crystallisation of pozzolanic products. The results indicate that with the exception of the gypsum-treated samples, the diffractograms of all other stabilised samples show a significant reduction in the peak intensity and basal reflections for clay minerals present in the soil. Reduction in peak intensity and basal spacing also indicates the reactivity of the clay minerals present in the soil with lime and cement. The reduction in intensity is more pronounced for quicklime stabilised samples (Fig 4.10).

In general terms, the diffractogram patterns of clay fractions of stabilised samples after 14 days moist curing show no clear evidence for the presence of crystalline pozzolanic products. This can be related to a number of factors; 1) the small total quantity and poor crystallinity of pozzolanic products, which makes them difficult to detect by XRD; 2) the diffractogram pattern of pozzolanic products may be overshadowed by the presence of calcite (due to its strong and close basal spacing with pozzolanic products in the stabilised soil), which results from the reaction of lime in the stabilised soil with CO_2 in the atmosphere). The crystallisation of calcite further suggested by the SEM results in Fig 4.13. 3) the research was conducted at low temperatures (20° C), whereas previous research by Croft (1964) suggests crystallisation of pozzolanic products favours elevated temperature; and 4) the relatively short curing time.

The reduction in peak intensity for quartz, feldspar and clay minerals suggests a general gradual destruction of their crystal lattice as a result of their reaction with lime or cement. This result is further supported by the results achieved in the study of the chemistry of stabilised samples, which indicates an increase in the percentage of K^+ in leachate from the stabilised soils as a result of the destruction of illite minerals (Table 4.2). Furthermore, XRD analysis on the mounts of clay fraction of 4% quicklime-treated sample were carried out to assess possibility of crystallisation of pozzolanic products after 90 days moist curing. The result (Fig 4.10) indicates

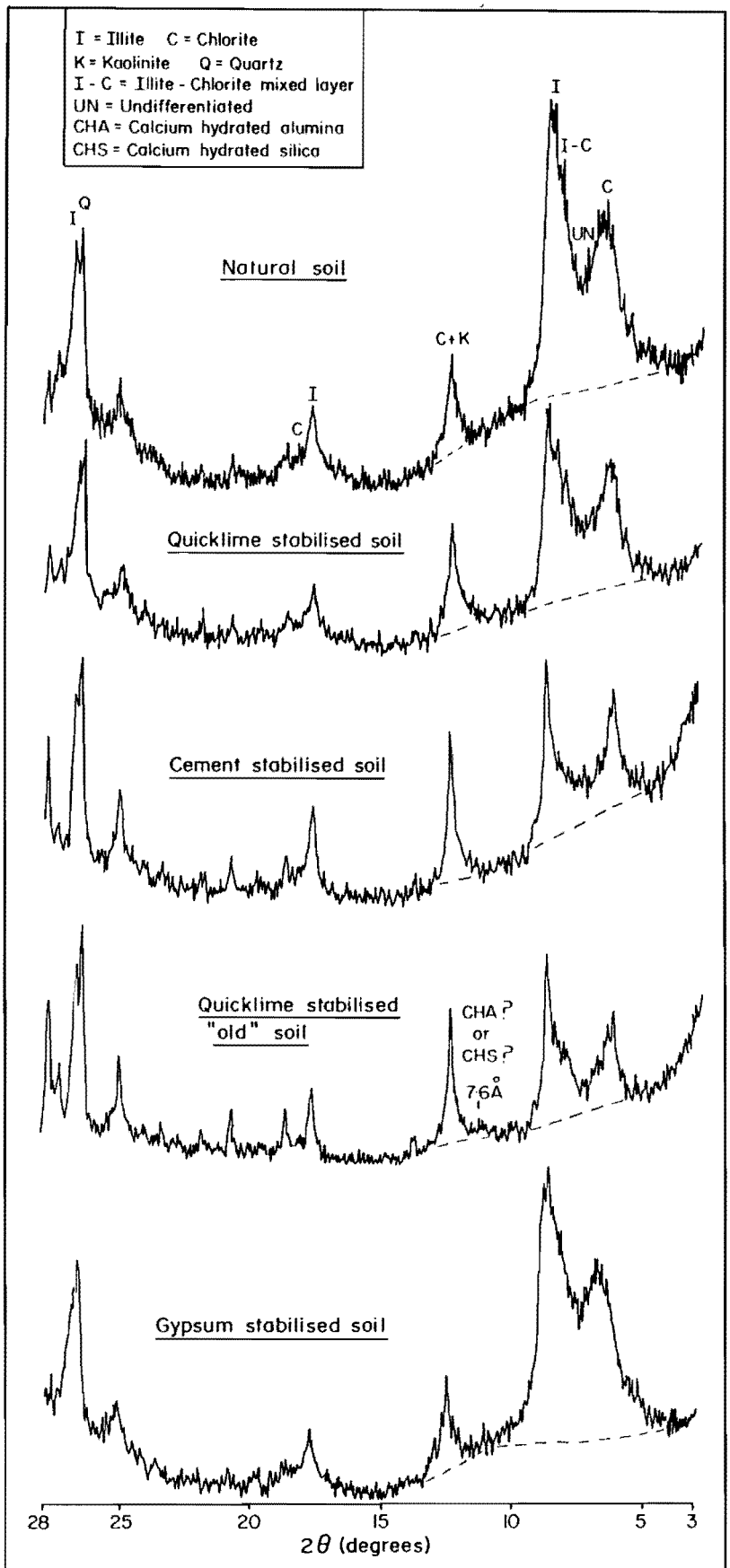


Figure 4.10 X-ray diffraction pattern of clay fraction of natural and chemically stabilised soil

(Note: all samples 14 days moist cured except "old" quicklime moist cured for 90 days)

tentative evidence for crystallisation of pozzolanic products (CHS and/or CHA).

ii) Bulk Fraction

XRD analyses of a powder sample of 4% quicklime stabilised sample after 90 days moist curing was analysed to assess the reactivity of quicklime with the non clay minerals in the soil, particularly quartz and feldspar, as well as to identify the presence of pozzolanic products. Figure (4.10) illustrates the diffractogram of the quicklime treated powder sample, and indicates a reduction in the intensity of quartz and feldspar peaks. A new phase of crystallisation of CHS and/or CHA can be observed, which produces a broad peak centering at 7.6 Å. Another peak at 7.4 Å can also be identified. In addition a peak at 2.63 Å were identified which indicates the presence of some unreacted lime (Fig 4.6).

In contrast with XRD analysis of the clay fraction after 14 days moist curing, XRD analysis of the bulk fraction after 90 days moist curing provides clear evidence of crystallisation of pozzolanic products. For example, evidence for crystallisation of pozzolanic products in the 90 days moist cured quicklime stabilised sample is indicated by the peak at 7.6 Å (Fig 4.6). The presence of unreacted lime gel in the diffractogramm of 4% quicklime stabilised sample after 90 days moist curing is indicated by the broad peak at 2.63 Å , (Fig 4.6) which suggests a slow rate of reaction between lime and the illitic loess soil.

4.3.3.2. SEM and EDAX Analyses

SEM analysis of the bulk fraction of quicklime, gypsum, and cement-treated samples after 90 days moist curing (99% relative humidity and 20° C) were carried out to find further evidence for crystallisation of pozzolanic products as suggested by the XRD results on the bulk fraction of the 90 day moist cured quicklime treated sample; and to identify the type of new minerals and assess their relationship to the soil fabric on the basis of SEM and EDAX results. SEM study for hydrated lime-treated samples was not carried out because of their similarity in chemical composition, and it is assumed that they have a similar effect on soil mineralogy.

i) Cement-treated Samples

SEM micrograph of the clay fraction of a cement-treated sample after 14 days moist curing in Fig 4.11 illustrates the presence of pozzolanic products as very fine fibres (width <0.1 μm) of poorly crystalline gel growing from the edge of illite minerals.

SEM micrograph of the bulk fraction in Fig 4.12 shows a sparse, scattered pattern of needle-like crystals as a result of the reaction of clay minerals (mainly illite) with Portland cement. Figure 4.13 illustrates these new minerals at higher magnification, and indicates that the minerals tend to interlock with each other. Diamond et al (1964) suggests this type of morphology is characteristic of calcium hydrated alumina. However, this morphology can belong to the ettringite minerals as well (Taylor, 1964). SEM results further indicate that the pozzolanic products seems to grow mainly from the edges of clay or non clay minerals. Figure 4.14 indicates the crystallisation of CHS and CHA occurs from the edge of plagioclase and clay minerals in the cement stabilised samples. In addition Fig 4.14 suggests that tobermorite gel exists as lath like sheets, calcium hydrated silica type (II) occurs as a bundles of fibres, and calcium hydrated alumina as long needle crystals. The elemental analyses of these minerals is given in Table (4.9). The EDAX analysis of pozzolanic products for the cement treated sample in Table (4.9) indicates a high proportion of silica (50%). This seems to be related to the concentration of silica in the unreacted plagioclase, as well as the combination of silica in pozzolanic products as shown in Fig 4.14. Table 4.9 further indicates a high concentration of calcium, which is mainly due to the presence of CHS and CHA in cement-treated samples (Fig 4.14). This is supported by a comparison of the concentration of Ca in the untreated soil (Table 4.8.) with the elemental analysis of pozzolanic products (Table 4.9), which shows a Ca concentration of 11%.

The SEM results (Fig 4.14) indicate that CHA minerals exist in fully crystalline form only in cement stabilised samples. The reason for this seems to be related to the presence of extra free alumina within the composition of the added Portland cement, which makes it more readily available for the production of this type of mineral.

Figure 4.13 illustrates the long needle like minerals which form at the edge of plagioclase and clay minerals from which they radiate outwards, and interlock with each other and minerals present at the soil. These may be related to CHA or ettringite minerals. This

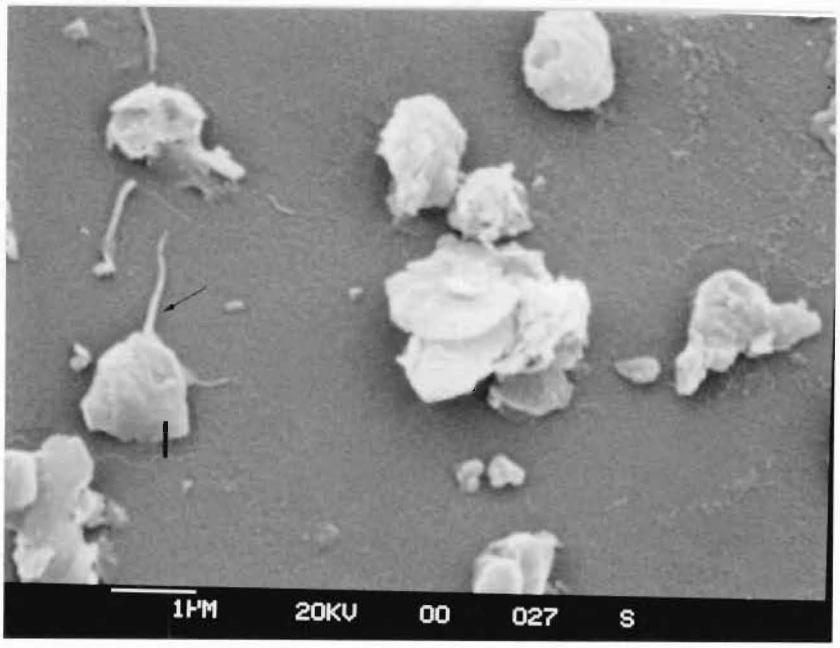


Fig 4.11 Clay fraction of cement-treated sample after 14 days moist curing (x 10,000). Note crystallisation of cementing agents as semi fibre form from the edge of illite(I).

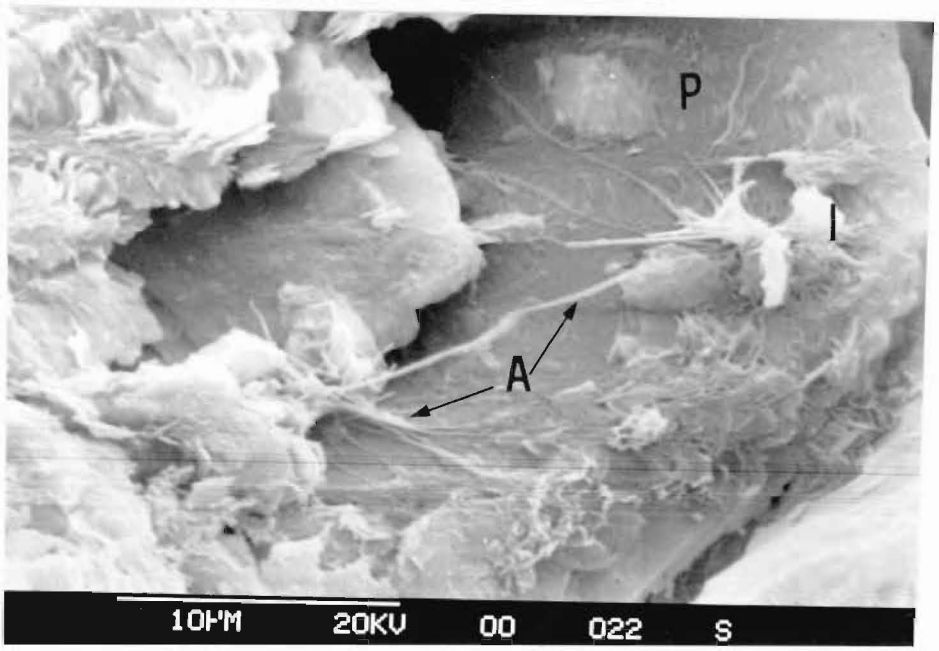


Fig 4.12 SEM micrograph of a crumb of cement-treated sample after 90 days moist curing (3,200). Note the growth of cementing agents (A) from the edge of illite (I) on the face of a plagioclase crystal(P).

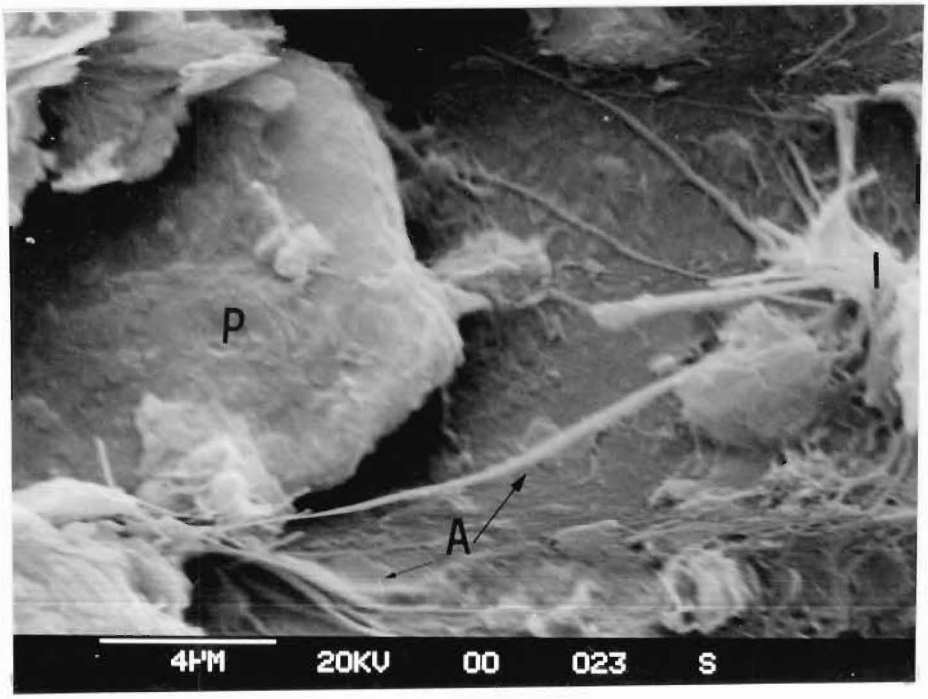


Fig 4.13 Pozzolanic products at (6,000) magnification from Fig 4.12. Note ettringite or CHA occurs as long fibrous needles (A).

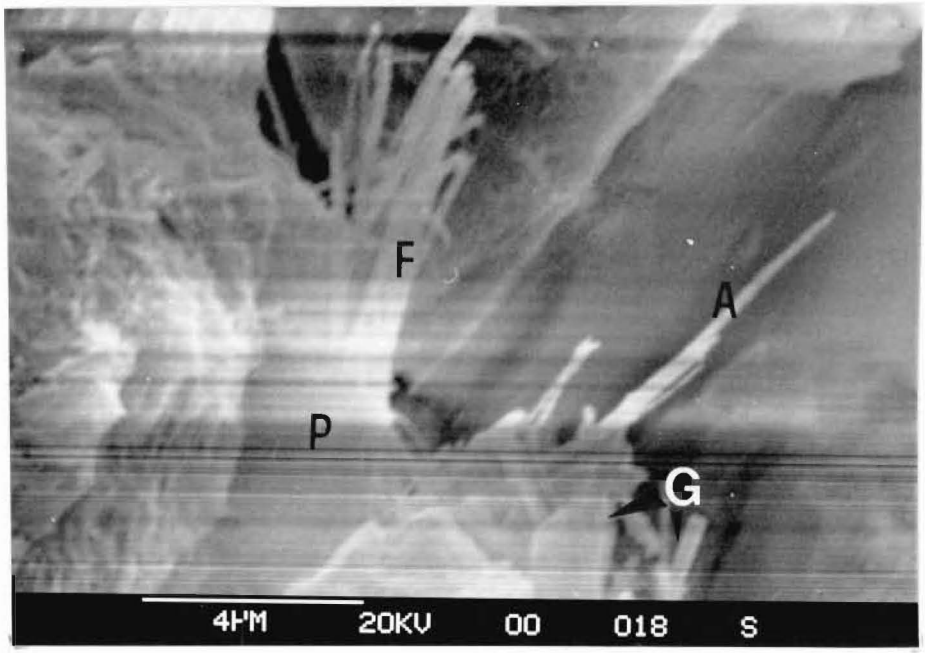


Fig 4.14 Pozzolanic products in a cement-treated samples (7,000) indicated by bundles of fibres(F) of CHS (II) growing from the edge of plagioclase (P). Also note the needle-like crystals (A) of CHA products, and lath like sheets of tobermorite gel (G).

type of fabric and mineralogy explains the very high increase in cohesion values in cement stabilised samples relative to the quicklime-treated and untreated samples (Fig 3.10). Due to the existence of gypsum within the chemical composition of Portland cement (Table 4.4), ettringite minerals can form. Ettringite is a highly hydrated calcium aluminate trisuphate (3 CaO . Al_2O_3 . 3 Ca SO_4 . 32 H_2O), that has a needle-like morphology and a large capacity to adsorb water which causes a strong expansion of its lattice. The pressure of expansion varied between 200-500 kN/m^2 in different clays. The presence of ettringite in cement-treated samples can be regarded as a factor contributing to the higher swelling potential of cement treated samples relative to quicklime and hydrated lime treated samples, (Section 2.8.3).

ii) Quicklime-treated Samples

The SEM micrograph of the clay fraction of a quicklime treated sample after 14 days moist curing indicate the crystallisation of rhombic calcite crystals and fibre curved form of tobermorite gel shown in Fig 4.15. SEM micrograph of the bulk fraction of a quicklime-treated sample after 90 days moist curing in Fig 4.16 illustrates the crystallisation of pozzolanic products as a "foil like" or "snow flake" crystals in quicklime treated samples. These type of morphologies usually belong to calcium hydrated silica type (I), (Diamond et al 1984). The higher magnification of CHS from Fig 4.16 is shown in Fig 4.17, and shows the new phase of crystallisation of CHS (I) occuring in the pore spaces between the soil grains.

Alumina is insufficiently available in the lime treated samples, mainly due to;

(1) the chemical composition of the added quicklime, which has no excess alumina (Table 4.3), and

(2) the tight structure of illite which prevents removal of alumina from the octahedral layer. These two factors prevent the formation of crystalline CHA in quicklime treated samples.

EDAX results on quicklime treated samples in Fig 4.17 is presented in Table (4.10) and indicates the presence of high percentages of silica and calcium elements. The ratio of silica to calcium is less than 2. This ratio of Si:Ca, along with the "foil like" morphology of the minerals, suggests the presence of CHS (I) in quicklime stabilised sample. Furthermore, the distribution of Si, Ca,

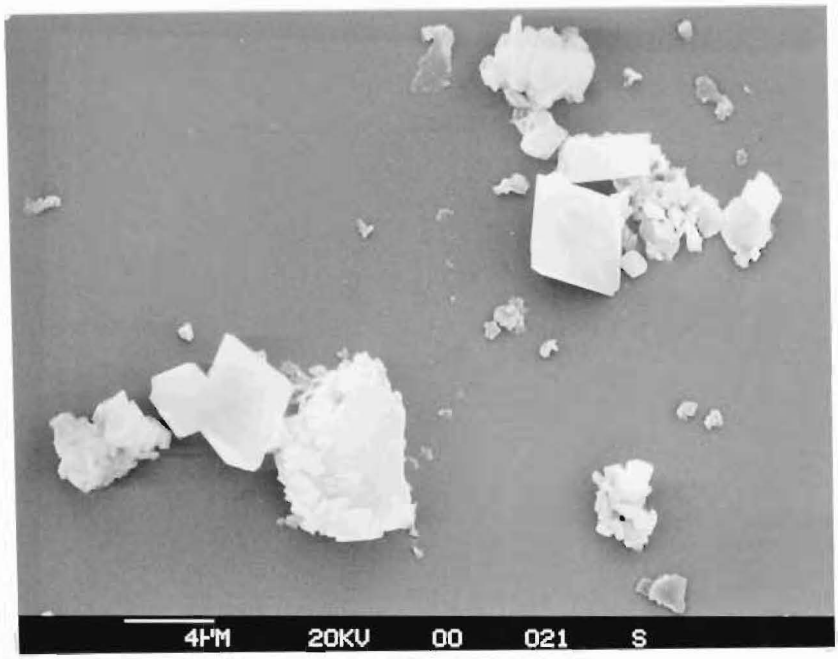


Fig 4.15 Clay fraction of quicklime-treated sample (x 5,500). Note the crystallisation of calcite in the rhombic form.

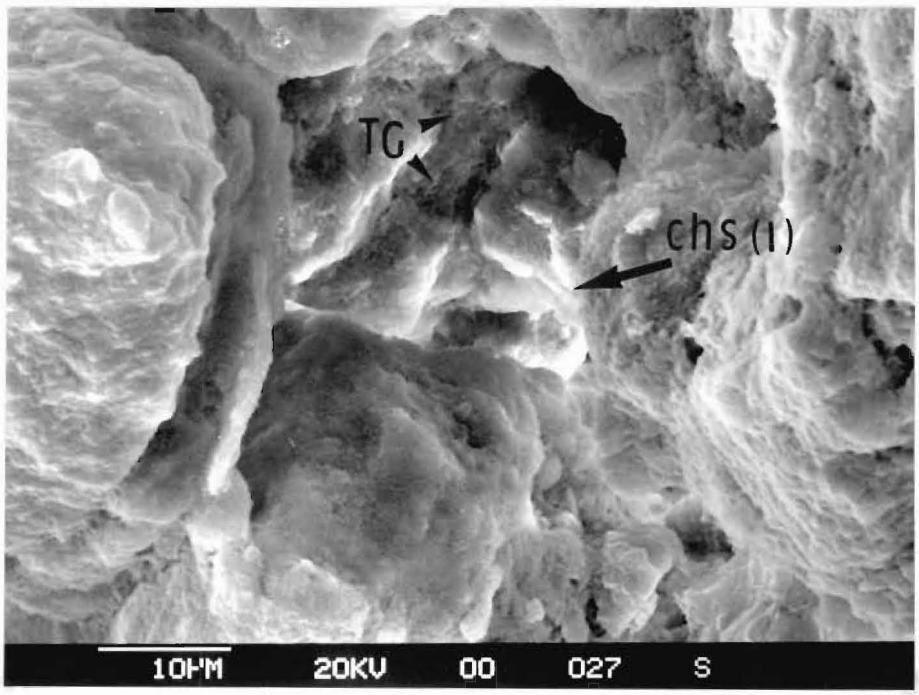


Fig 4.16 The crystallisation of "foil like" CHS (I) and Tobermorite gel (TG) in the quick-lime stabilised sample (x 1,700).

Table 4.10 Elemental distribution of pozzolanic product from SEM micrograph of quicklime-treated sample in Fig 4.17.

ELEMENT	WEIGHT PERCENT
Al	8.32
Si	22.60
Ca	12.03
K	3.70
Na	0.44
P	3.15
S	1.17

Al elements for the whole micrograph in Fig 4.17 indicates the high concentration of Si and Ca in the centre of the EDAX micrograph (Figures 4.19 and 4.20), which correlates with the position of the CHS(I) minerals in the SEM micrograph. The very high concentration of Si, Ca, Al, on the left hand side of the EDAX micrograph (Fig 4.18 to 4.20), correlates with the presence of a plagioclase crystal.

The study of soil fabric in the 4% quicklime treated sample (Fig 4.21) indicates that there is a significant reduction in the distribution and pore sizes between soil grains. Pores sizes are reduced mainly as a result of the crystallisation of pozzolanic products, particularly CHS (I). The Tobermorite gel and CHS (I) act as cementing agents which bond the soil grains together. These bonding properties of cementing agents result in increases in cohesion and the angle of internal friction values for quicklime treated samples relative to untreated samples (Table 3.1 and 3.3). The bonding action of cementing agents in quicklime treated samples also improves the physical properties of stabilised samples by providing a reduction in erodibility, slaking and swelling potential relative to the untreated sample.

The presence of unreacted lime (existing as "gel" like material) around the edge of quartz and feldspar grains (Figure 4.21) may produces a reduction in friction, unconfined compressive strengths and shear strength values as well as an increase in the strain values of 4% quicklime treated samples. The mechanism of reduction in friction and unconfined compressive strength values could be related to "gel" material acting as a lubricant and enabling grains to slide relative to each other, resulting in lower values of friction and unconfined compressive strength compared with samples treated with a 2% concentration of stabiliser (Table 3.1 and 3.3).

iii) Gypsum-treated Samples

SEM study on the clay fraction of gypsum-treated sample after 14 days moist curing shows no evidence of crystallisation products, but does show the flocculation of clay minerals (Fig 4.22).

SEM Micrograph of the bulk fraction of gypsum-treated sample after 90 days moist curing in Fig 4.23 shows also flocculation of clay minerals with no significant changes on their morphology. Overal there is a slight reduction in pore size distribution relative to that of the untreated sample (Fig 4.7). The higher magnification of a quartz

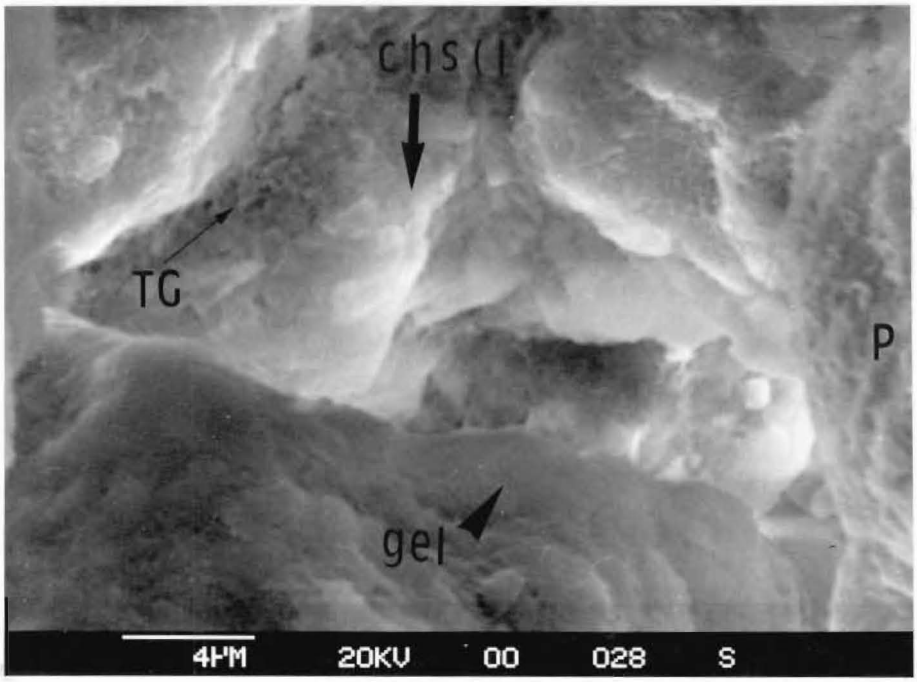


Fig 4.17 High magnification (x 4,000) of CHS from Fig 4.16. Note the presence of unreacted lime "gel".

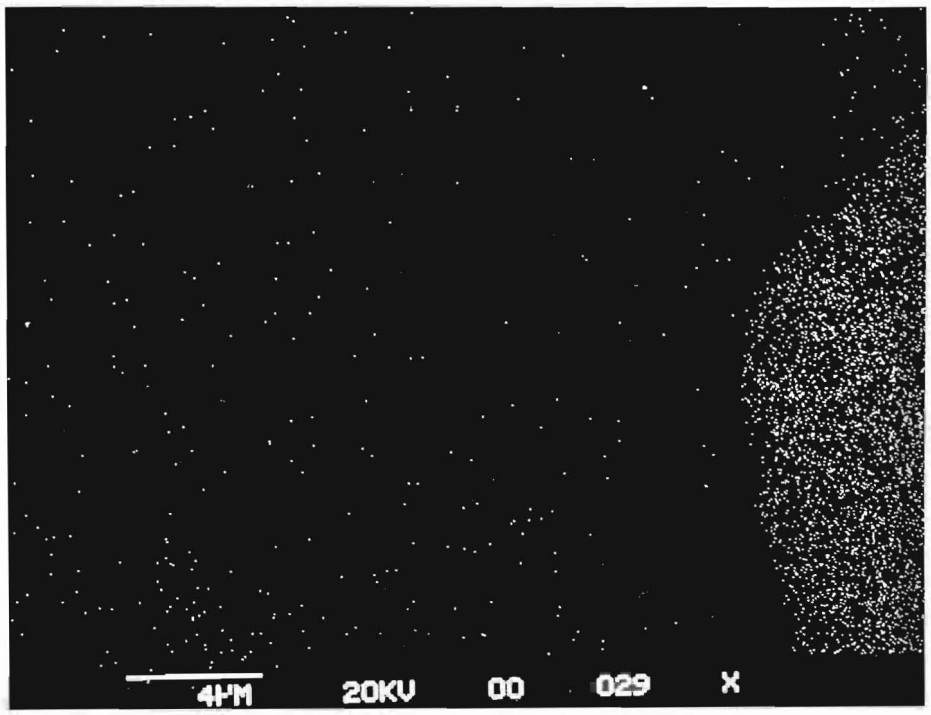


Fig 4.18 Elemental distribution of Silica for quicklime-treated sample on Fig 4.17.

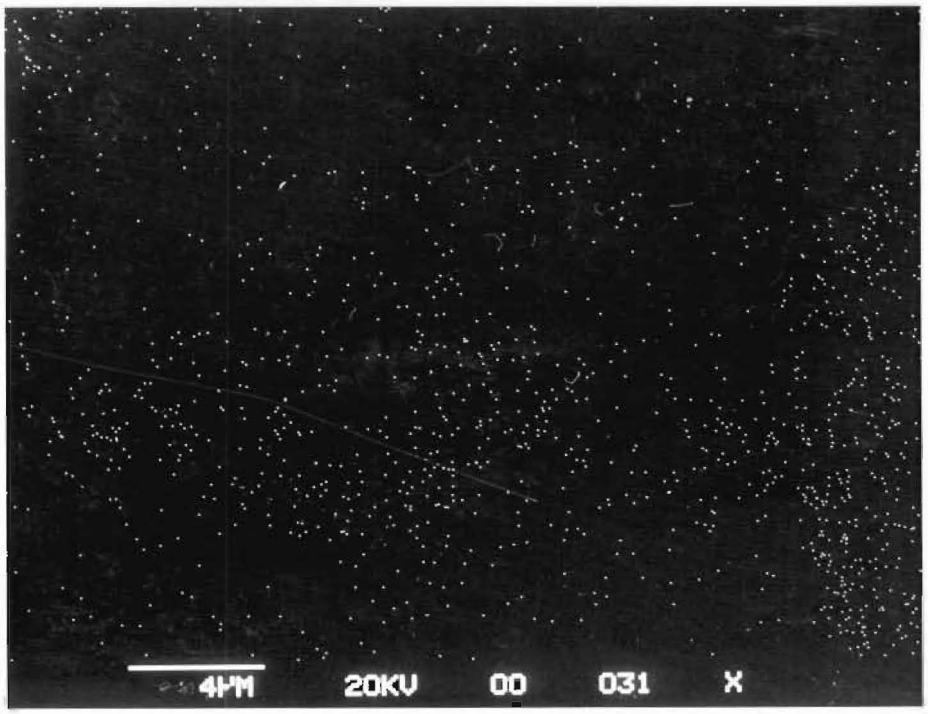


Fig 4.19 Elemental distribution of calcium for quicklime-treated sample on Fig 4.17.

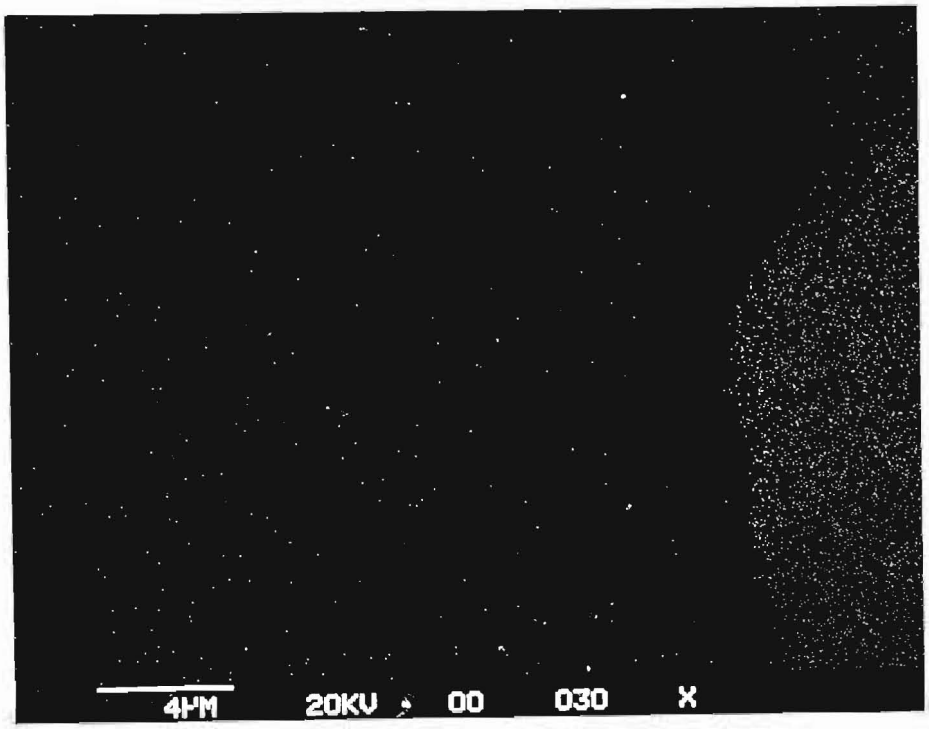


Fig 4.20 Elemental distribution of alumina for quicklime-treated sample on fig 4.17.

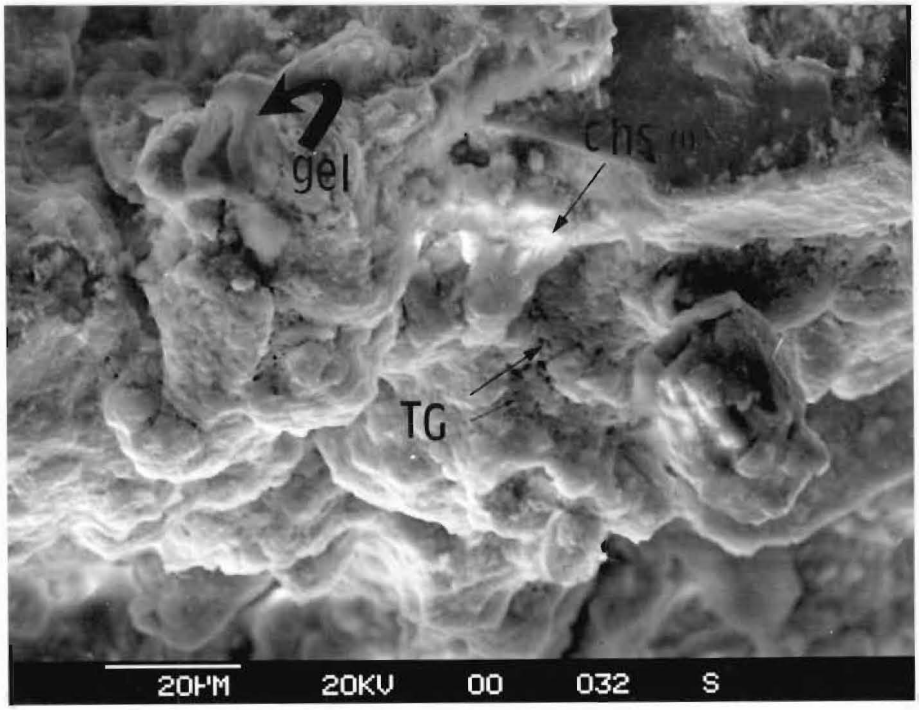


Fig 4.21 Soil fabric of quicklime-treated sample as related to the distribution of Tobermorite gel (TG) and the crystallisation of CHS(I). Also note the presence of unreacted lime"gel" around the edge of quartz and feldspar grains (thick arrow).

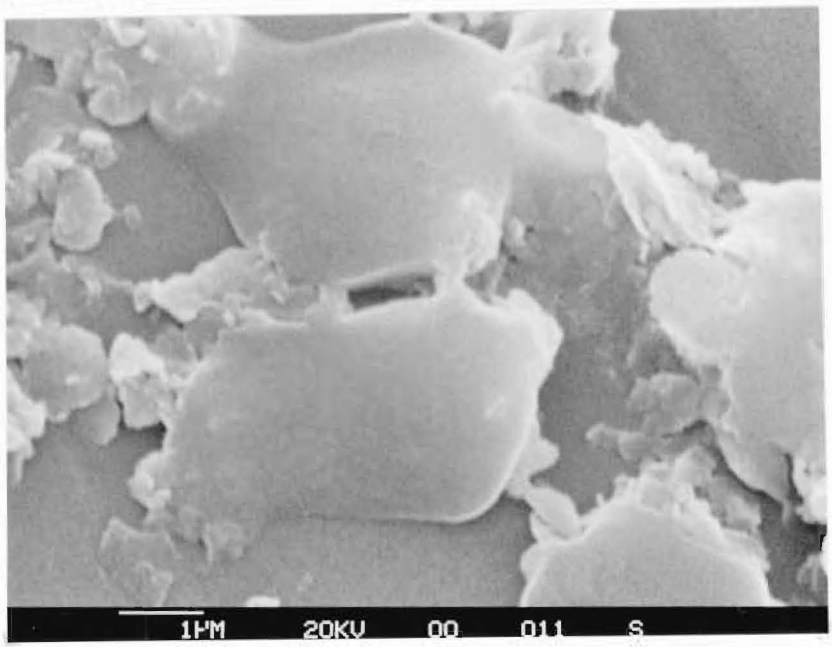


Fig 4.22 Clay fraction of gypsum-treated sample (x 10,000) showing the flocculated clay minerals.

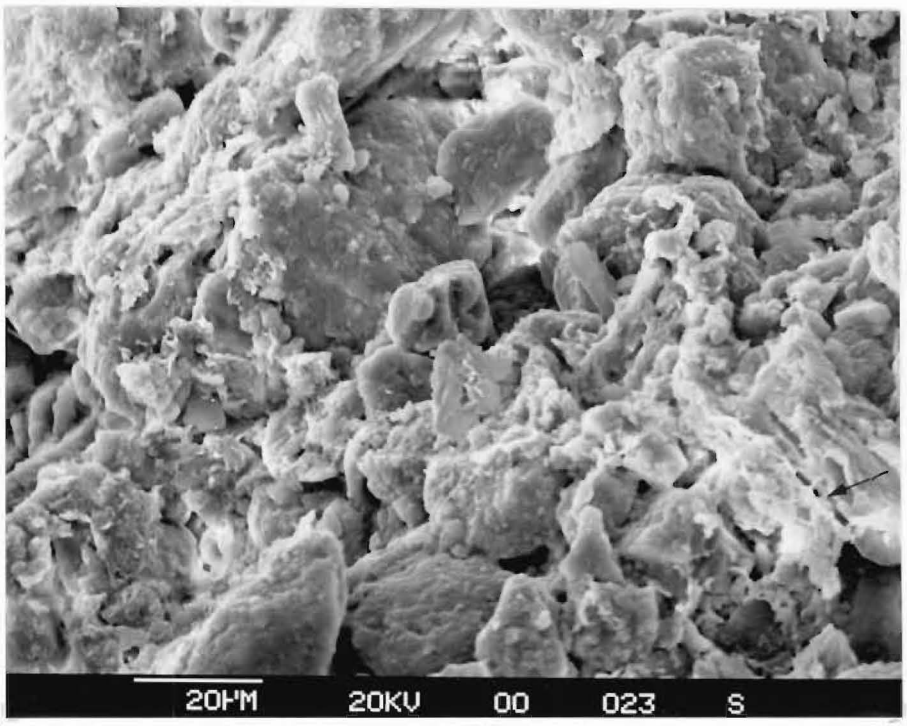


Fig 4.23 SEM micrograph shows an overall view of soil fabric of gypsum-treated sample (x 800). Note the flocculation of clay minerals

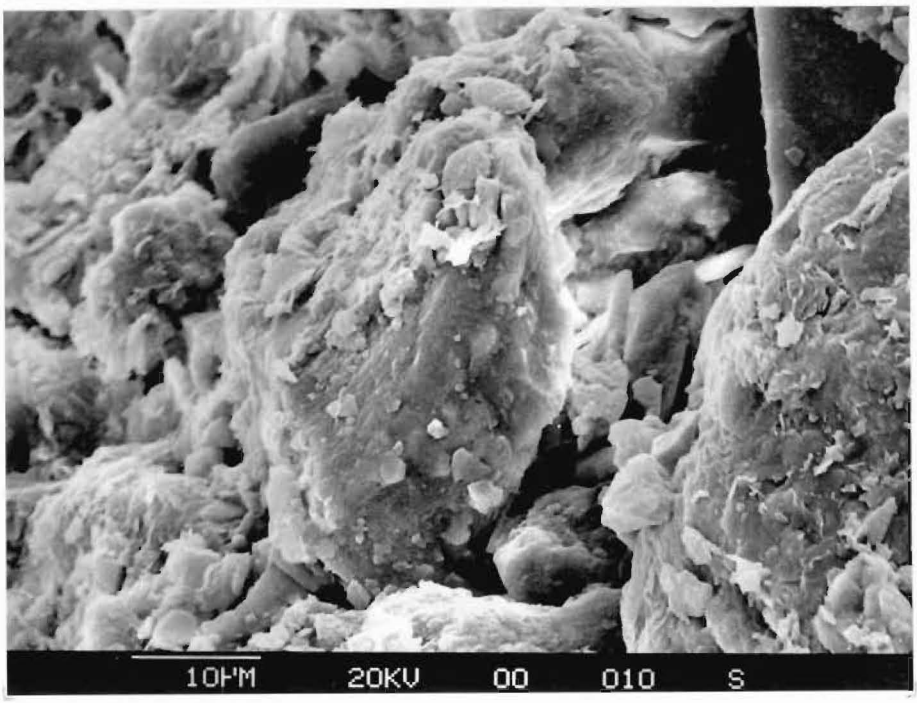


Fig 4.24 Gypsum-treated sample shows lack of evidence of pozzolanic products (x 1,600). Note quartz and plagioclase are remain unaffected.

crystal in Fig 4.24 indicates there is no reaction between non-clay minerals and gypsum after 90 days moist curing at 99% relative humidity and 20° C.

4.4. Synthesis

On the basis of the chemical and mineralogical study of natural and stabilised samples the following conclusions can be drawn.

1) The low organic carbon content, low soluble salt concentration in pore water, and high values of S.A.R, $_{p}H$, and E.S.P are important factors controlling the dispersive characteristics of loess soil.

2) XRD and SEM analysis indicate that the natural soil mainly consists of silt size quartz and feldspar grains, while illite is the dominant clay mineral.

3) Study of soil fabric indicates an almost uniform distribution of relatively small pore size, as well as a lack of natural cohesive cement between the grains. These can be regarded as factors contributing to the slaking, erodibility and swelling potential of loess soil.

4) XRD analysis and the SEM study in particular have indicated the crystallisation of cementing agents (CHS gel, CHS (I), CHS (IT) and CHA) as a result of the reaction between lime and cement with clay minerals, quartz, feldspar and other potential sources of alumina or silica within the soil.

5) The chemical composition of Portland cement enables a greater variety of pozzolanic products to form, while quicklime stabilised samples produce a smaller variety of pozzolanic products (consisting mainly of CHS (I) and Tobermorite gel).

6) The presence of untreated hydrated lime gel in 4% quicklime stabilised samples after 90 days moist curing (as suggests by XRD and SEM results) is indicative of a slow rate of reaction between lime and illite types of soil, and suggests that 2% concentrations of quicklime are more suitable for short term increase in soil strength (but not necessarily in the long-term).

7) SEM study of soil fabric of cement and quicklime stabilised samples indicates firstly that there is a significant reduction in the distribution and sizes of pores between the quartz and feldspar grains, the pores being infilled by fine fibres of tobermorite gel as well as by the crystallisation of CHS (I) as within the pores. Secondly, it

can be seen that plagioclase and quartz grains are bonded by cementing agents, and this bonding action is considered to be the main factor causing an improvement in physical and engineering properties of lime and cement treated samples.

8) The chemical and mineralogical study of gypsum stabilised samples have indicated that there is no reactivity between gypsum and soil minerals, although it acts as flocculant material.

CHAPTER FIVE: Summary and Conclusions

5.1 Loess Erodibility

Dispersive and erodible loessial soils of Bank Peninsula display a variety of mass movement and erosion features. The dispersive and erodible nature of some loess soils in the Whaka Terrace subdivision has resulted from the following properties;

1) soil chemistry, specifically a low organic carbon content, low soluble salts concentration in pore water, high concentration of exchangeable sodium cations in the soil, and soil alkalinity, which together provide a suitable situation for deflocculation and dispersion of the clay minerals present.

2) Grainsize Distribution, the loess soil mainly consists of a silt size fraction of quartz and feldspar grains with 12-14% clay content, which results in a weakly bonded soil skeleton.

3) Soil Fabric, the presence of small pores (10-15 um), as well as a lack of natural cohesive cement between the soil grains (as suggested by the SEM study), providing conditions for slaking during saturation.

Chemical stabilisation techniques using quicklime, Portland cement, hydrated lime, gypsum and a mixture of gypsum and hydrated lime (in a 1:1 ratio) have been adopted to reduce and/or prevent further erosion by rendering the soil non-dispersive, non-erodible and durable under wetting and drying conditions.

5.2. Laboratory Stabilisation Trials

5.2.1 Test Methods

Index and physical properties of both untreated and chemically stabilised loess-colluvium samples were analysed using:

1) Standard (proctor) compaction; 2) grainsize analysis; 3) Atterberg limits; 4) falling head permeability; 5) Emerson Crumb dispersion; 6) Sherard pinhole erodibility; 7) slaking; and 8) uniaxial swelling tests.

Strength characteristics of treated and untreated samples were determined using unconfined compressive strength tests and undrained shear box tests.

The chemistry of both treated and untreated samples were studied using:

1) organic carbon content; 2) soluble salt concentration; 3) cation exchange capacity; 4) x-ray fluorescence analyses; and 5) $_{p}H$ determination. The mineralogy of samples was studied using 1) x-ray diffraction, 2) scanning electron microscope, and 3) energy dispersion x-ray analyses.

5.2.2. Physical and Index Properties Changes

With the application of 1, 2, 4% quicklime, hydrated lime, gypsum, Portland cement, and a mixture of gypsum and hydrated lime (in a 1:1 ratio) after 14 days moist curing (at 99% relative humidity and 20°C), the following changes in the physical properties of stabilised loess-colluvium were observed:

1) Optimum moisture content of compacted stabilised soil increased from 13% for untreated sample to 13.5-16.5% for stabilised samples, while maximum dry density decreased from 1.86 tm^{-3} for untreated samples to 1.80-1.72 tm^{-3} for stabilised samples. The effect is greatest for cement-treated samples and least for gypsum-treated samples.

2) The sand size fraction of the stabilised soil increases from 10% for untreated samples, to 12-30% for stabilised samples, which corresponds to a reduction in silt and clay content. The effect is greatest for samples treated with quicklime, and least for soils treated with gypsum.

3) With the application of 1% and 2% of all stabilisers used (except gypsum), the plasticity index increases from 7 for untreated sample to 8-10 for stabilised samples, while at a 4% concentration of stabiliser the plasticity index decreases from 10 to 8. Gypsum has no effect on the plasticity index.

4) The coefficient of permeability of all stabilised samples increases (20-100 times relative to untreated samples), while compacted density decreases from 2.06tm^{-3} to 1.92 tm^{-3}. The effect is greatest for quicklime-treated samples, and least for gypsum-treated samples.

5) Application of hydrated lime and quicklime at 1% concentration produces a non-dispersive, non-erodible and durable material, which sustained 5 cycles of wetting and drying (one cycle consist of 4 hours of wetting and 20 hours of drying). The effect of Portland cement on the dispersion/erosion, slaking and swelling potential of the loess-colluvium soils is similar to those of

hydrated lime and quicklime, but higher concentrations (2-4%) are required than for the lime. Application of gypsum at 4% concentration produces a non-dispersive material, however it has no effect on erodibility, slaking and swelling potential of the untreated loess. A mixture of gypsum and hydrated lime cannot produce durable material, and samples possessed a high swelling potential and slaked completely after the first cycle of wetting and drying.

5.2.3. Strength Characteristics

With the application of 1, 2, 4% of the above chemical stabilisers after 14 days moist curing, the following changes in the strength characteristics of loess-colluvium were observed:

1) At 1% and 2% concentration of all stabilisers the unconfined compressive strength increases from 210 kPa for untreated sample to 250-750 kPa for stabilised samples. The effect is greatest for cement and quicklime stabilised samples and the least for gypsum-treated samples. The unconfined compressive strength at 4% concentration of stabilisers decreases, although strength values at the 4% level are still higher than the strength values obtained for untreated samples. The reduction in strength of treated samples at 4% concentration is greatest for gypsum and cement-treated samples, and least for quicklime-treated samples.

2) All stabilised samples (except gypsum-treated samples) possess lower dry density (1.76 tm^{-3} for untreated sample and 1.54-1.73 tm^{-3} for stabilised samples), but greater unconfined compressive strength relative to the untreated samples. The maximum compressive strength for hydrated lime, quicklime, and cement stabilised samples at each concentration (1, 2, and 4%) of stabilisers is correlated with those specimens possessing the greatest dry densities.

3) With the application of 1 and 2% of each stabiliser, the strain at peak strength reduces from 2.8% for untreated sample to 2.3-1.1 % for stabilised samples. The effect is greatest for soils treated with quicklime and Portland cement, and least for soils treated with gypsum. At 4% concentration of all stabilisers the strain values increase.

4) Modulus of elasticity of all stabilised samples at 1 and 2% levels increases by 18 to 100 times relative to the untreated samples. At 4% concentration of all stabilisers the modulus of

elasticity decreases, but the treated samples still possess a greater modulus of elasticity (8-32) than the untreated samples. The reduction in modulus of elasticity of 4% stabilised samples is greatest for gypsum-treated samples, and least for quicklime-treated samples.

5) With the application of 1 and 2% of all stabilisers used (except gypsum) the angle of internal friction (ø) of stabilised samples increases by 3 to 6 ° from 39° for untreated sample to 41-45 ° for stabilised samples, while at 4% concentration of stabilisers a reduction in ø values (2°) was observed.

6) With the application of all the stabilisers (except gypsum), cohesion values increase from 31 kPa for untreated samples to 47-90 kPa for stabilised samples. Samples treated with 4% mixed stabiliser (gypsum and hydrated lime in a 1:1 ratio) had the highest cohesion values (90 kPa).

5.2.4. Chemical and Mineralogical Changes

Mineralogical study of quicklime, gypsum, and Portland cement stabilised samples after 14 days moist curing indicates that;

1) With the exception of gypsum stabilised samples, the cation exchange capacity for all other stabilised samples increases from 7.3 me.% to 8.72-10.16 me.%. The effect is greatest for 4% quicklime-treated samples.

2) The $_{p}H$ of all stabilised samples other than gypsum increases from 7.6 for the untreated sample to between 12.1 and 12.6 for treated samples.

3) SEM study of soil fabric of stabilised samples suggested that there is a reduction in the distribution and sizes of pores between the quartz and feldspar grains, as a result of crystallisation of cementing agents which also bond the soil grains.

4) XRD analyses and the SEM study in particular show the crystallisation of cementing agents (tobermorite gel, calcium hydrated silica type (I) and (II), calcium hydrated aluminate and ettringite) in 90 days moist cured cement-treated samples. Gypsum-treated samples show no reaction between gypsum and minerals present in the soil, but do show flocculation of clay minerals.

5.3. Conclusions and Recommendations

5.3.1. Principal conclusions

1) $_{p}H$ measurement can be regarded as a quick reference test to assess the potential for reaction between a soil and a stabiliser. It was noted that a pozzolanic reaction between a soil and a potential stabiliser can only take place in a high $_{p}H$ environment.

2) The $_{p}H$ value of a chemically stabilised soil provides an indication of optimum lime and/or cement content for achieving maximum strength in the chemical stabilisation techniques. Optimum lime or cement content is reached when a further increase of stabiliser does not increase the $_{p}H$ value of a soil/stabiliser mixture above a certain level (12.5).

3) Mineralogical study of untreated and chemically stabilised samples provides a basis for comparison of changes in physical properties and strength characteristics of the treated and untreated samples that are due to the formation of cementing agents.

4) Although shear strength is maximised in samples treated with a mixture of gypsum and hydrated lime, it fails to provide a durable material which is the prime objective in chemical stabilisation of Port Hills Loess. Pure hydrated lime does, however, produce a durable material, therefore there is no benefit in mixing the two stabilisers.

5) The application of Portland cement produces a similar result to that of hydrated lime and quicklime but at higher concentrations (2-4%).

6) Laboratory results show that 1-2% hydrated lime and quicklime-treated samples are non-erodible, non-dispersive and durable. The effects on physical properties and strength are more pronounced with quicklime than hydrated lime, however the former is potentially more hazardous in practical application.

5.3.2. Further investigations

1) The effect of lime carbonation on the strength properties of lime and cement-treated samples needs further investigation.

2) The use of slurried instead of powdered lime in stabilisation of Port Hills Loess requires further investigation.

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APPENDICES

APPENDIX :1 TERMINOLOGY

A1.1 Soil material description

A1.2 Rock material description

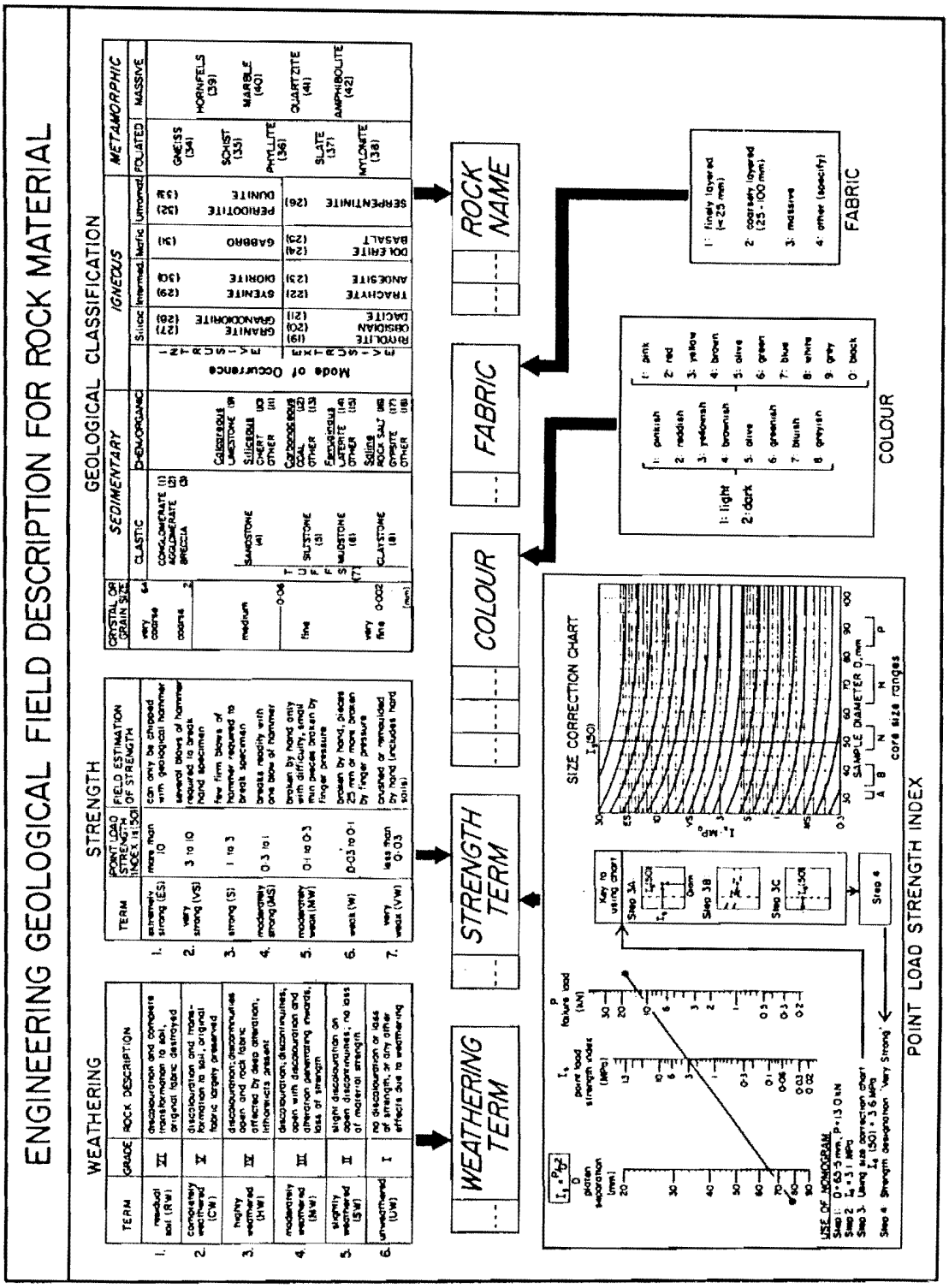


Figure A1.2 Rock material description terminology .

(from Bell and Pettinga, 1984)

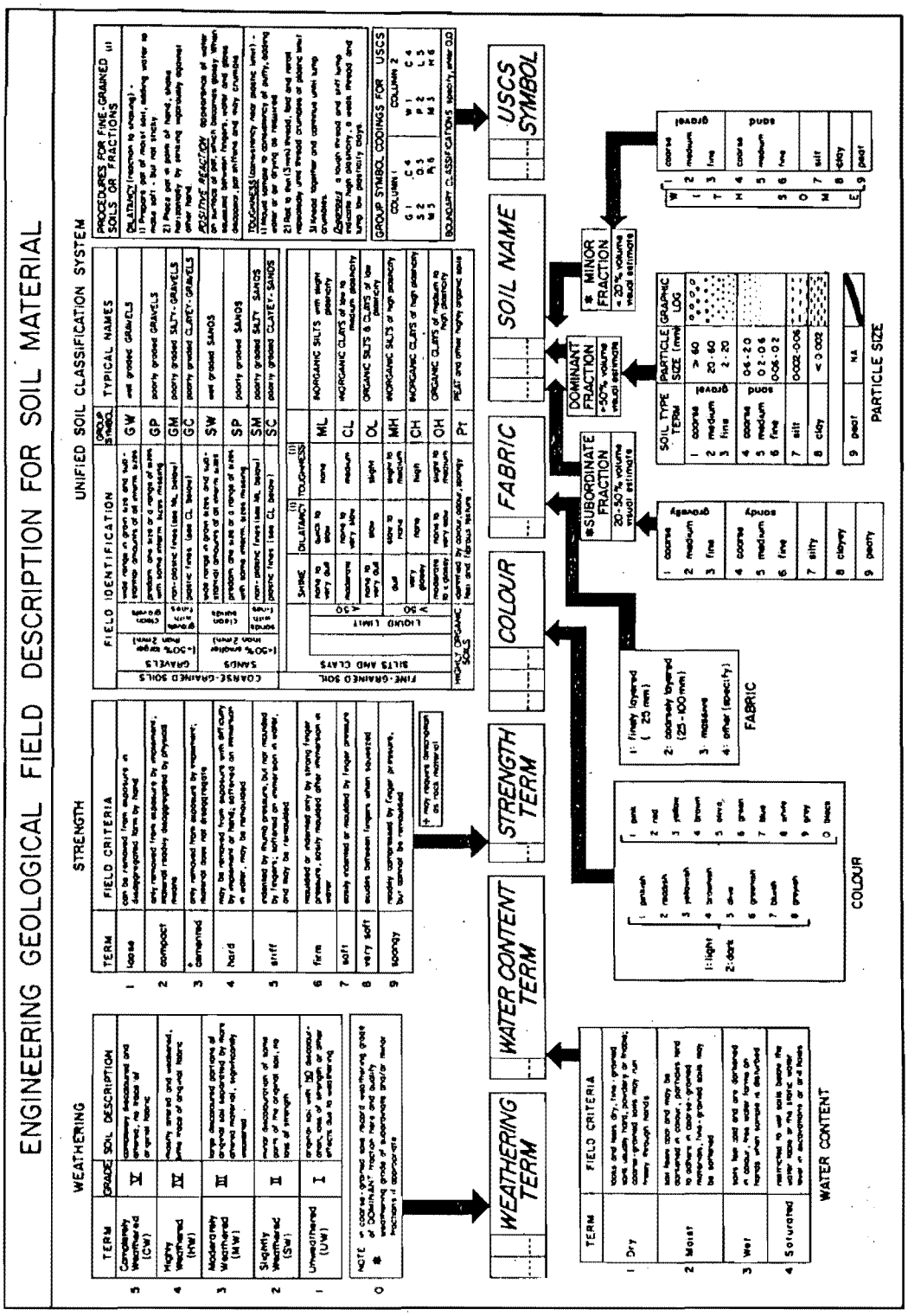


Figure A1.1 Soil material description terminology .

(from Bell and Pettinga, 1984)

APPENDIX: 2 MISCELLANEOUS SOIL TESTS

A2.1 Determination of Moisture Content

A2.2 Determination of In-situ Density

A2.3 Dry Density/ Moisture Content Relationship

A2.4 Determination of Atterberg Limits

A2.1. Determination of Moisture Content

New Zealand standard 4402 part 1 (1980) test 1, pp 15-17.

A2.2. Determination of In-situ Density

New Zealand standard 4402 part 2 (1981) test 17 (c), pp 40-42.

A2.3. Dry Density/Moisture Content Relationship

Test Procedure

New Zealand standard 4402 part 2 (1981) test 14, pp 16-19.

Modification

The same 2.5 kg of sample was used for each test.

Test Result

Figure A2.1 shows the effect of each stabiliser on OMC and dry density.

A2.4. Determination of Atterberg Limits

Liquid limit

New Zealand standard 4402 part 1 (1980) test 2, pp 18-23.

Plastic limit

New Zealand standard 4402 part 1 (1970) test 3, pp 24-26.

Plastic Index

New Zealand standard 4402 part 1 (1980) test 4, p 27.

Test Result

Figure A2.2 Illustrates the effect of each stabiliser on plasticity and activity of loess-colluvium bulk sample.

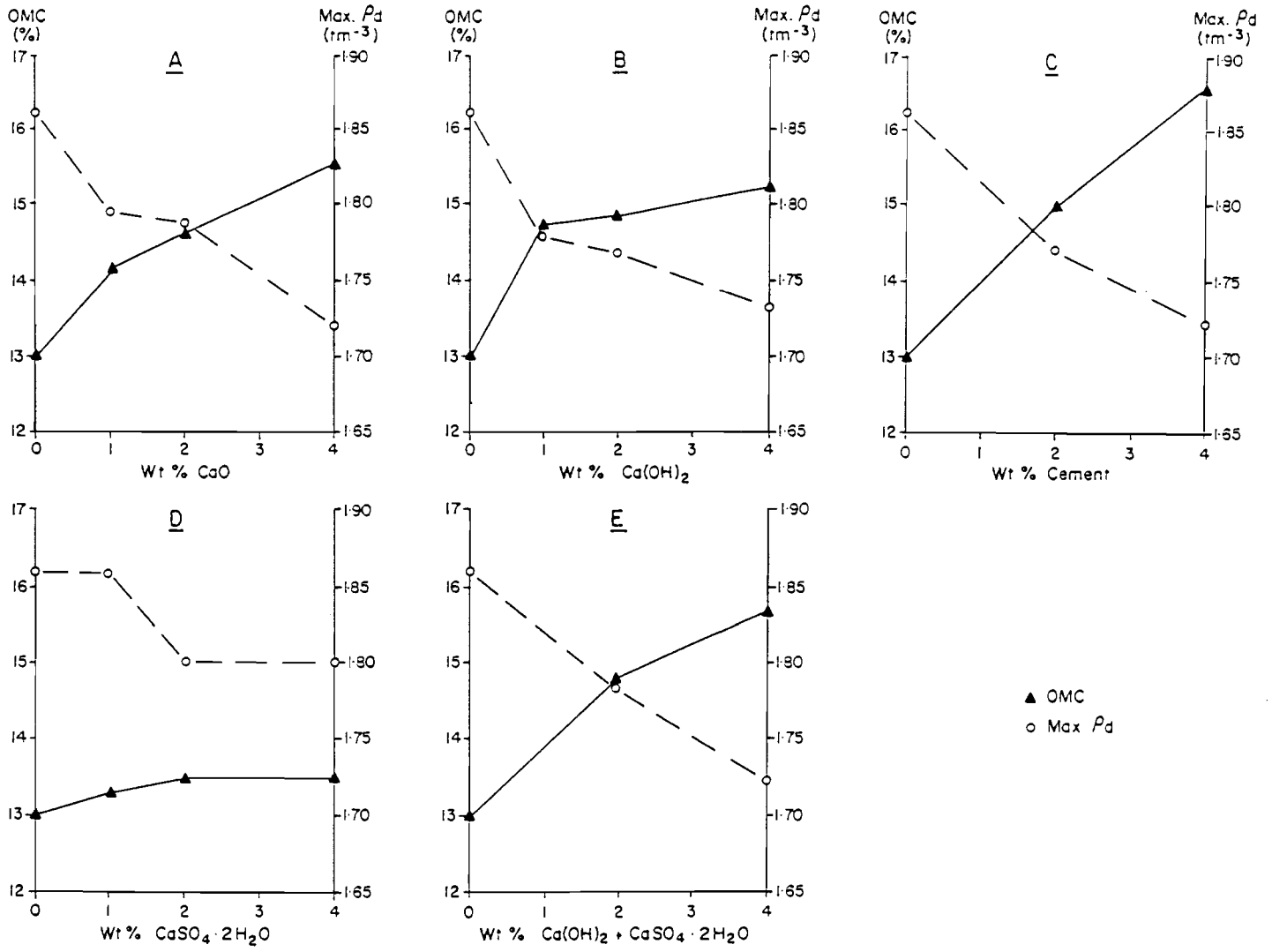


Figure A2.1 Effect of stabiliser on moisture/density relationships for A - quicklime, B - hydrated lime, C - cement, D - gypsum, E - gypsum and hydrated lime.

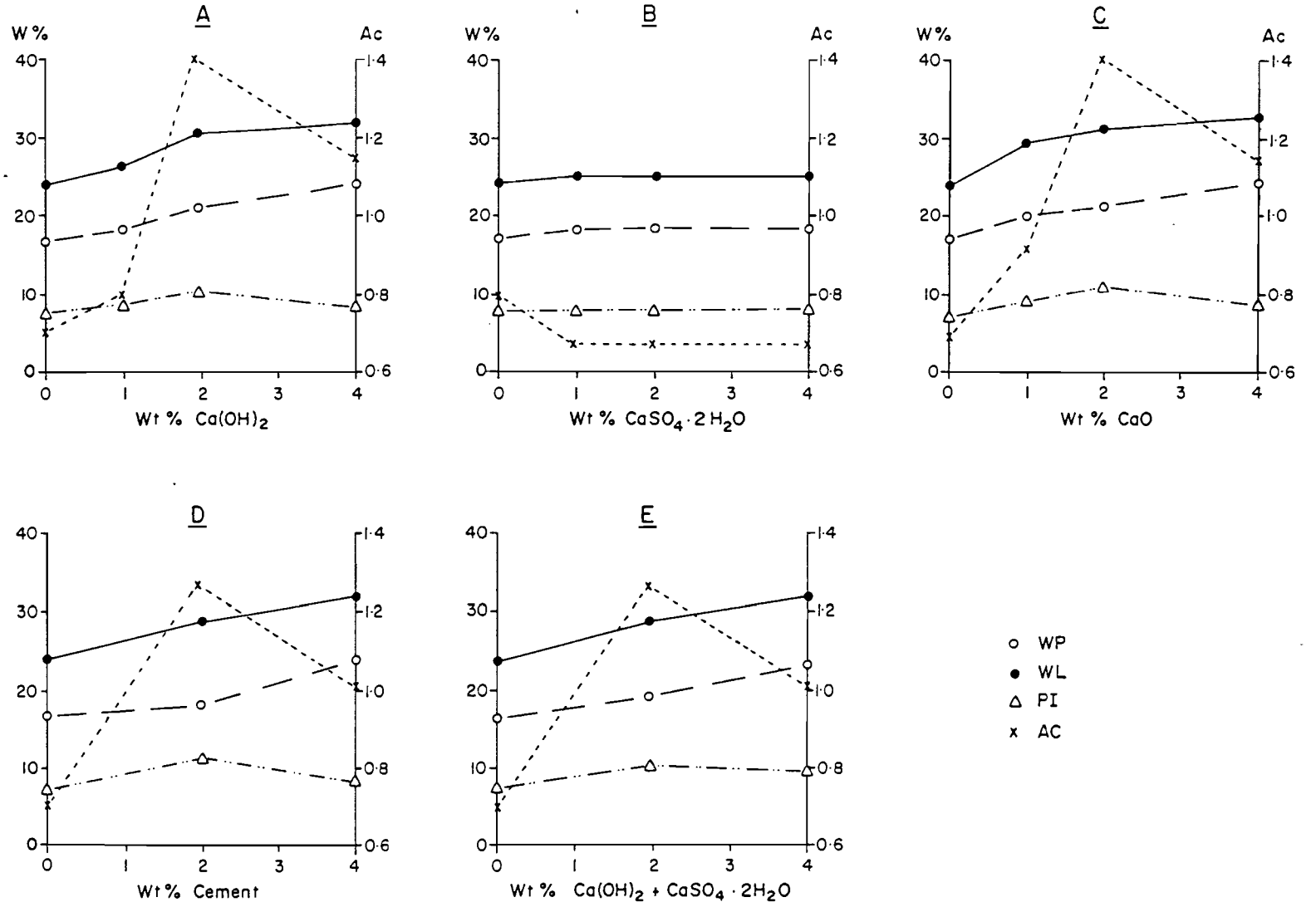


Figure A2.2 Effect on plasticity and activity of: A - hydrated lime, B - gypsum, C - quicklime, D - cement, E - gypsum and hydrated lime.

APPENDIX: 3 GRAINSIZE ANALYSES

A3.1 Test Methods

A3.2 Test Results

A3.1. Test Methods

Dry sieve and hydrometer analyses for the sand and mud fractions respectively were carried out according to the N.Z. standards 4402, (part one tests 9B and 9D).

Two tests were performed for each sample and the results averaged. To overcome flocculation problems the following concentrations of calgon were added to the 30-40 g of stabilised samples.

For 1% stabiliser 20-40 cc calgon at 50 g/l
For 2% stabiliser 80 cc calgon at 50 g/l and
For 4% stabiliser 100 cc calgon at 50 g/l.

A3.2. Test Results

Grainsize curves for each treated and untreated sample are summarised in Figs A3.1 - A3.15. The effect of stabiliser on the clay, silt and sand fractions of Whaka Terrace loess are summarised in Fig A3.16

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT ..WHAKA TERRACE.... SAMPLE NO . 0% (FIELD SAMPLE). SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..SUBDIVISION..... LOCATION ...PORT HILLS..... DATE ..... DATE .....

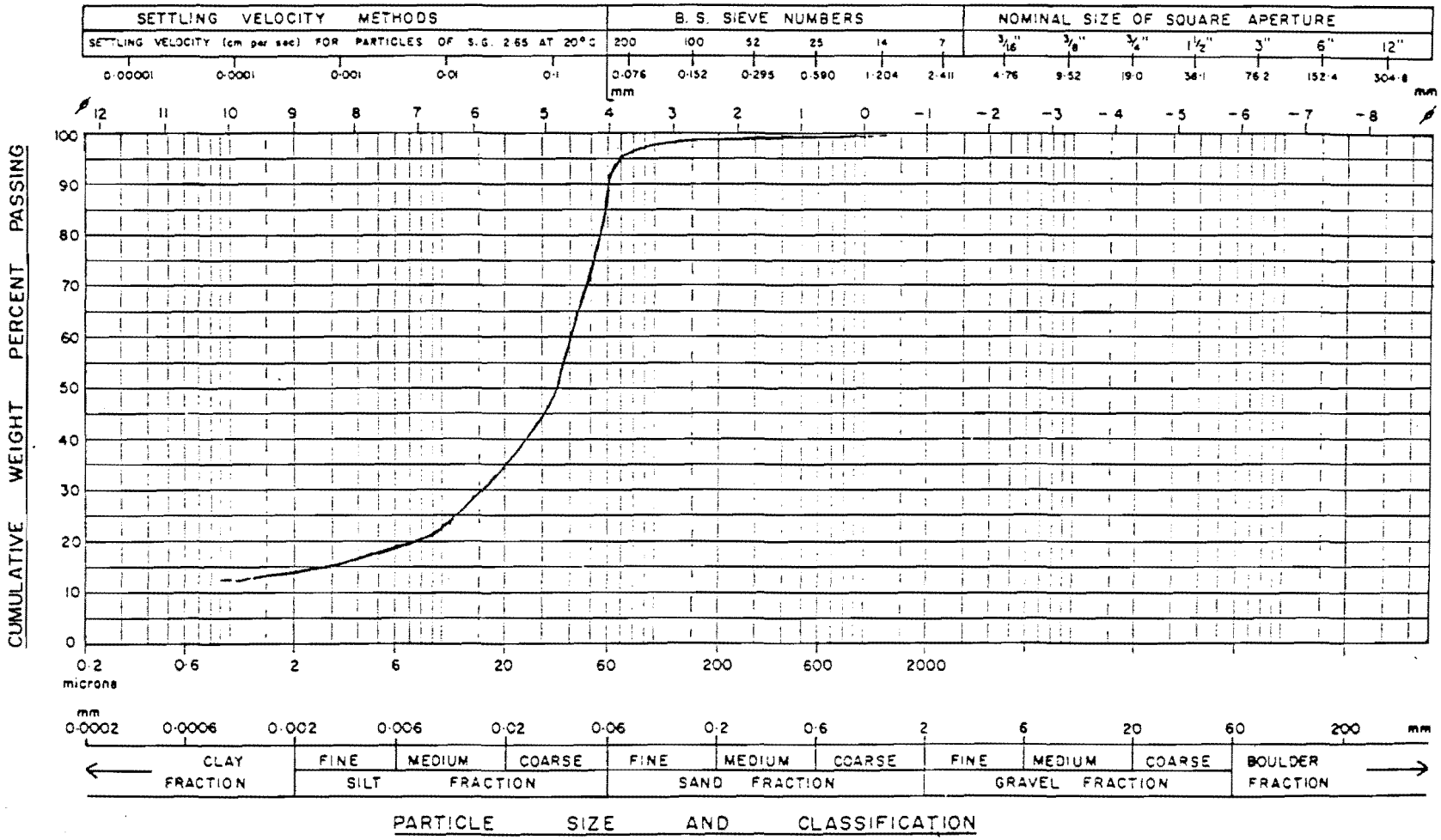
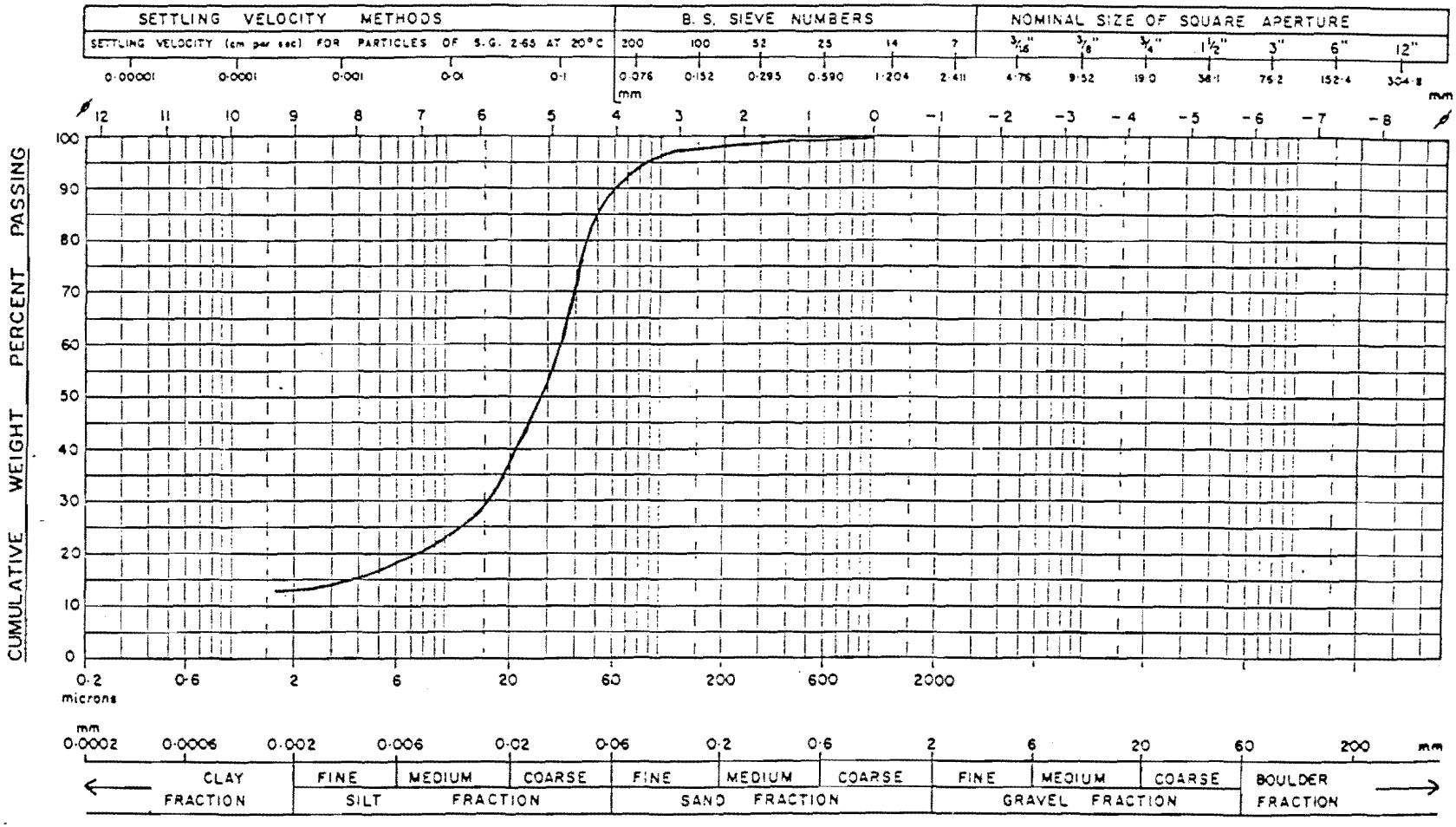


FIGURE A3.1 Grainsize distribution curve for untreated sample.

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WHAKA TERRACE . SAMPLE NO 0% (MOIST CURED). SAMPLED BY ..... ANALYSED BY SIEVE & HYROMETER

SUBDIVISION ..... LOCATION ...PORT HILLS..... DATE ..... DATE .....



PARTICLE SIZE AND CLASSIFICATION

Figure A3.2 Grainsize distribution curve for untreated moist_cured sample

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WHAKA TERRACE SUBDIVISION ..... SAMPLE NO 1% GYPSUM-MC ... SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION ... PORT HILLS ..... DATE ..... DATE .....

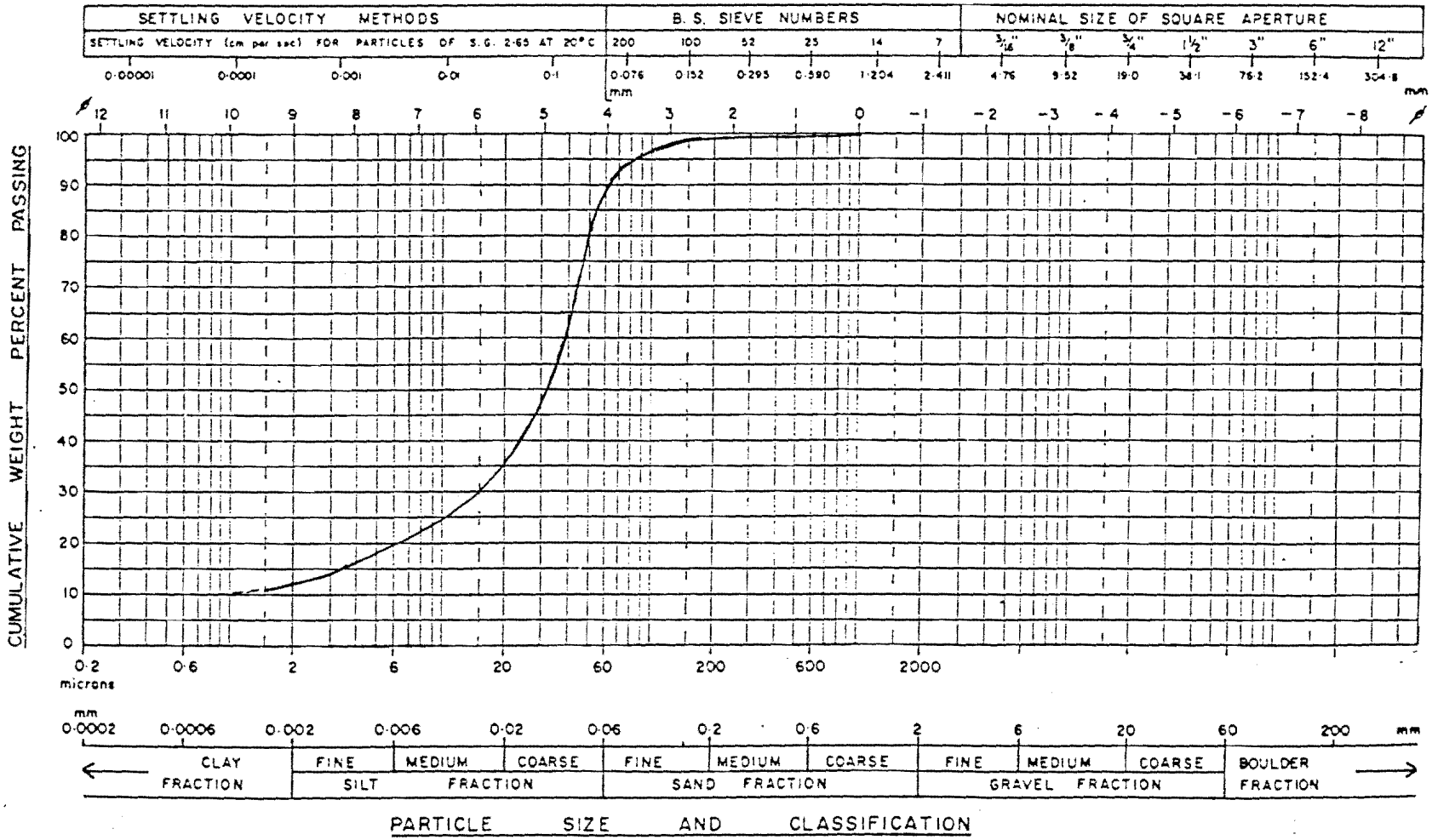


Figure A3.3 Grainsize distribution curve for 1% gypsum-treated sample.

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WHAKA TERRACE SUBDIVISION SAMPLE NO 2% GYPSUM + MC SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION ... PORT HILLS ..... DATE ..... DATE .....

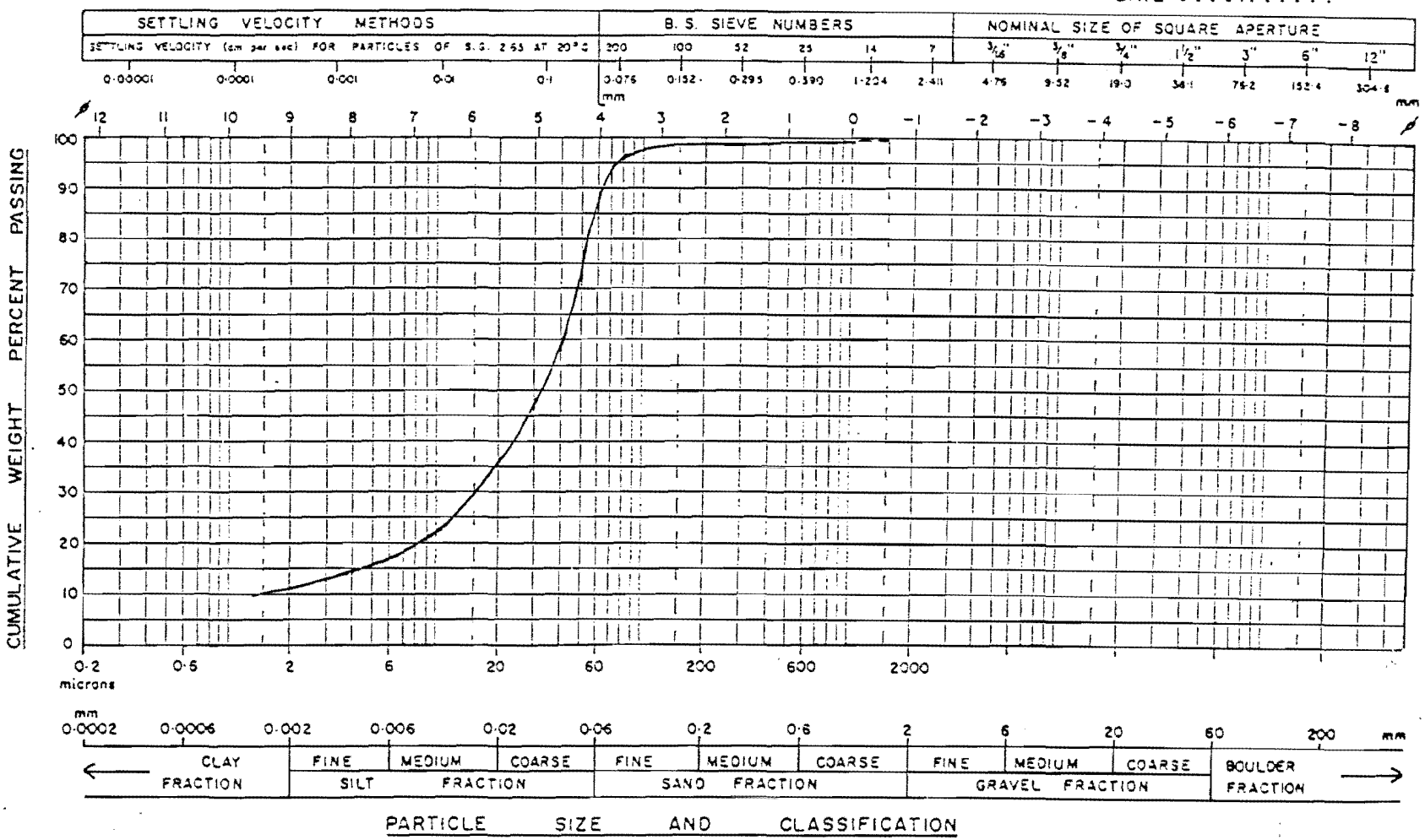


Figure A3.4 Grainsize distribution curve for 2% gypsum _ treated sample

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WHAKA TERRACE SUBDIVISION. SAMPLE NO 4% GYPSUM-MC. SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION ... PORT HILLS ..... DATE ..... DATE .....

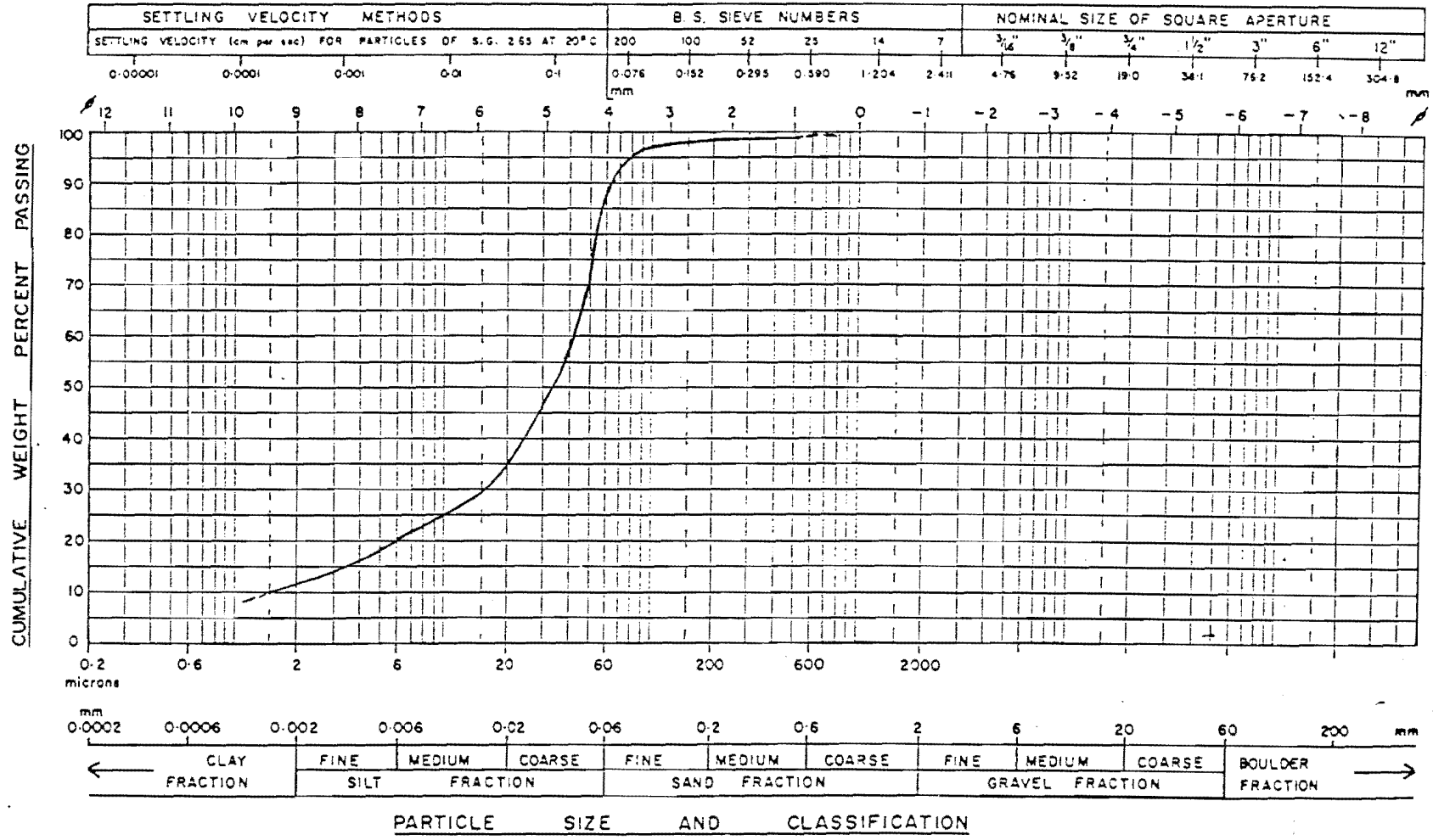
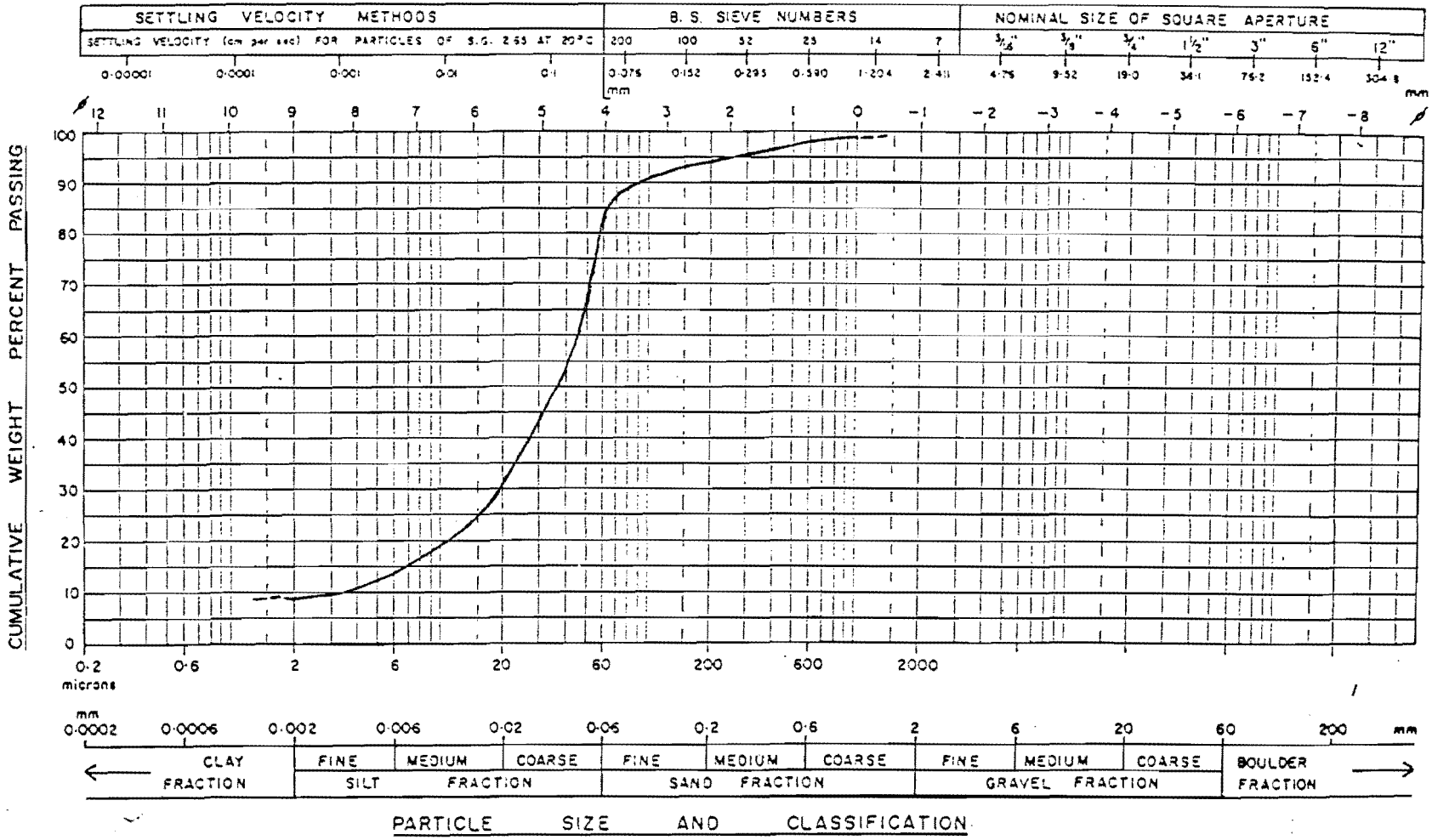


Figure A3.5 Grainsize distribution curve for 4% gypsum-treated sample.

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT HIHAKA TERRACE SUBDIVISION SAMPLE NO 1% QUICKLIME: MC SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION ... PORT HILLS ..... DATE ..... DATE .....



PARTICLE SIZE AND CLASSIFICATION

Figure A3.6 Grainsize distribution curve for 1% quicklime treated sample

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WHAKA TERRACE SUBDIVISION SAMPLE NO 2% QUICKLIME - MC SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION ..... PORT HILLS ..... DATE ..... DATE .....

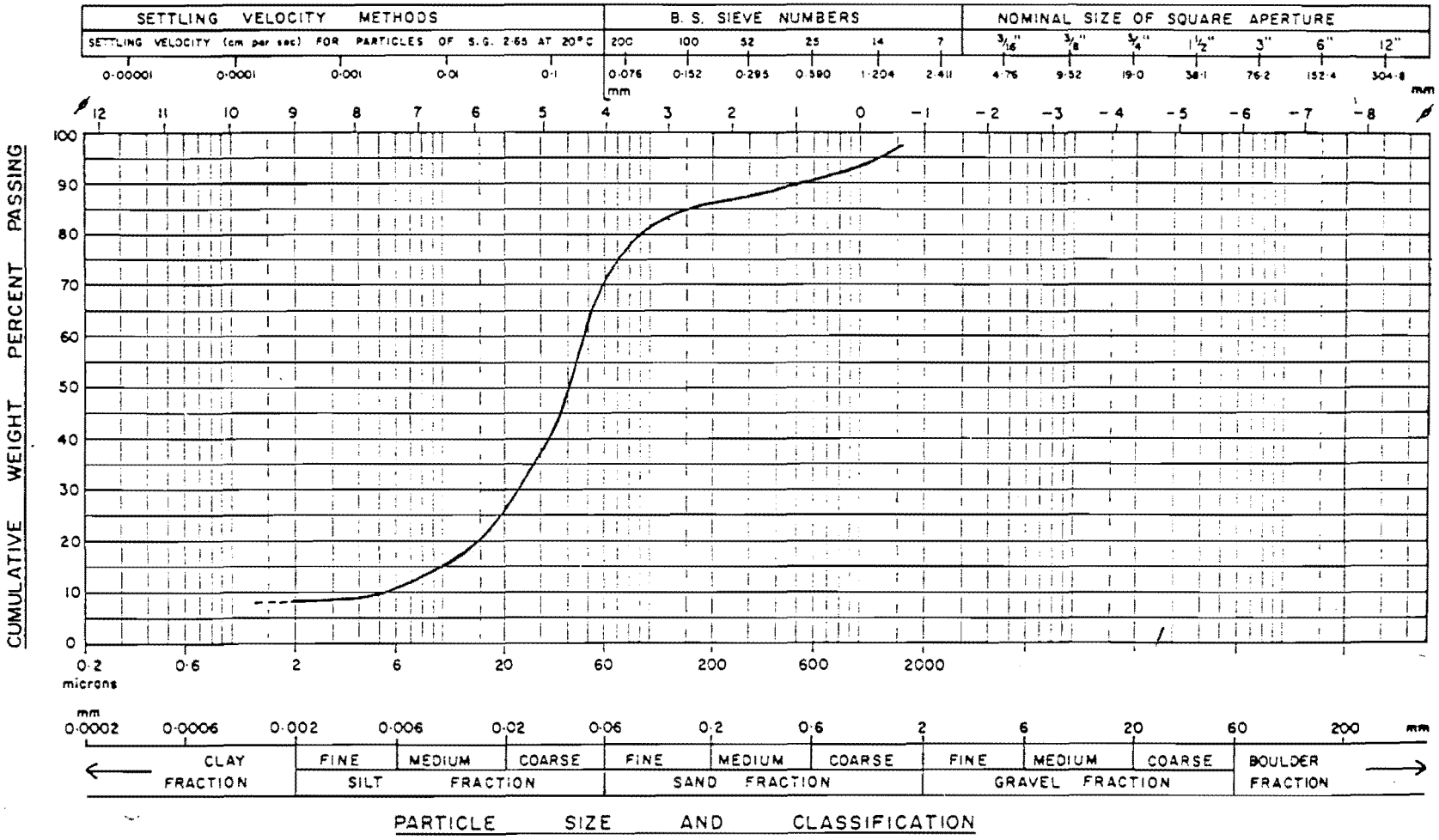


Figure A3.7 Grainsize distribution curve for 2% quicklime treated sample

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WHAKA TERRACE SUBDIVISION SAMPLE NO 4% QUICKLIME-M.C. SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION ..... PORT HILLS ..... DATE ..... DATE .....

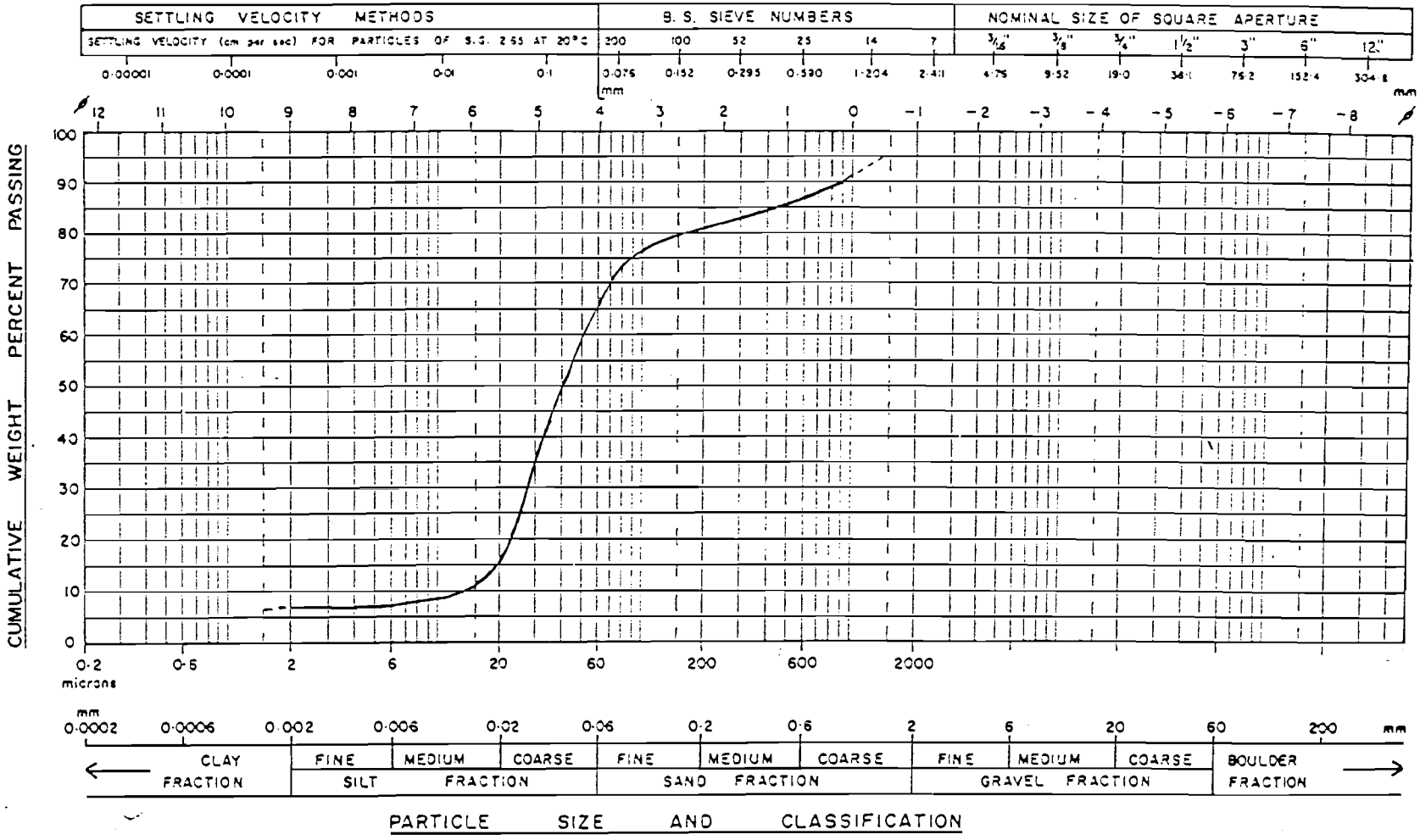
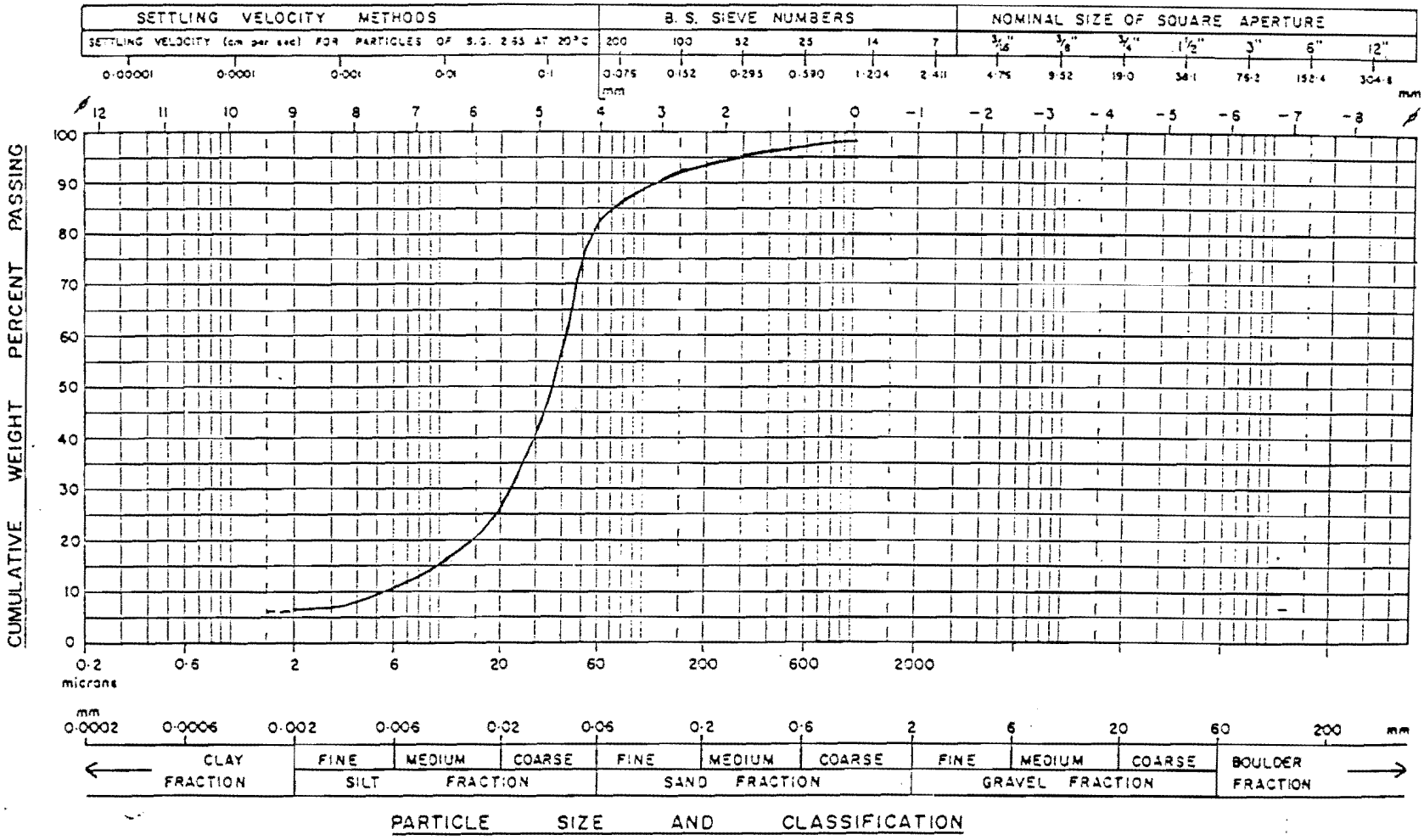


Figure A3.8 Grainsize distribution curve for 4% quicklime treated sample

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WAIKA TERRACE SUBDIVISION SAMPLE NO 1% HYRATED LIME SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION ... PORT HILLS ..... DATE ..... DATE .....



PARTICLE SIZE AND CLASSIFICATION

Figure A3.9 Grainsize distribution curve for 1% hydrated lime treated sample

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WAKA TERRACE SUBDIVISION ... SAMPLE NO 2% HYDRATED LIME SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION ... PORT HILLS ..... DATE ..... DATE .....

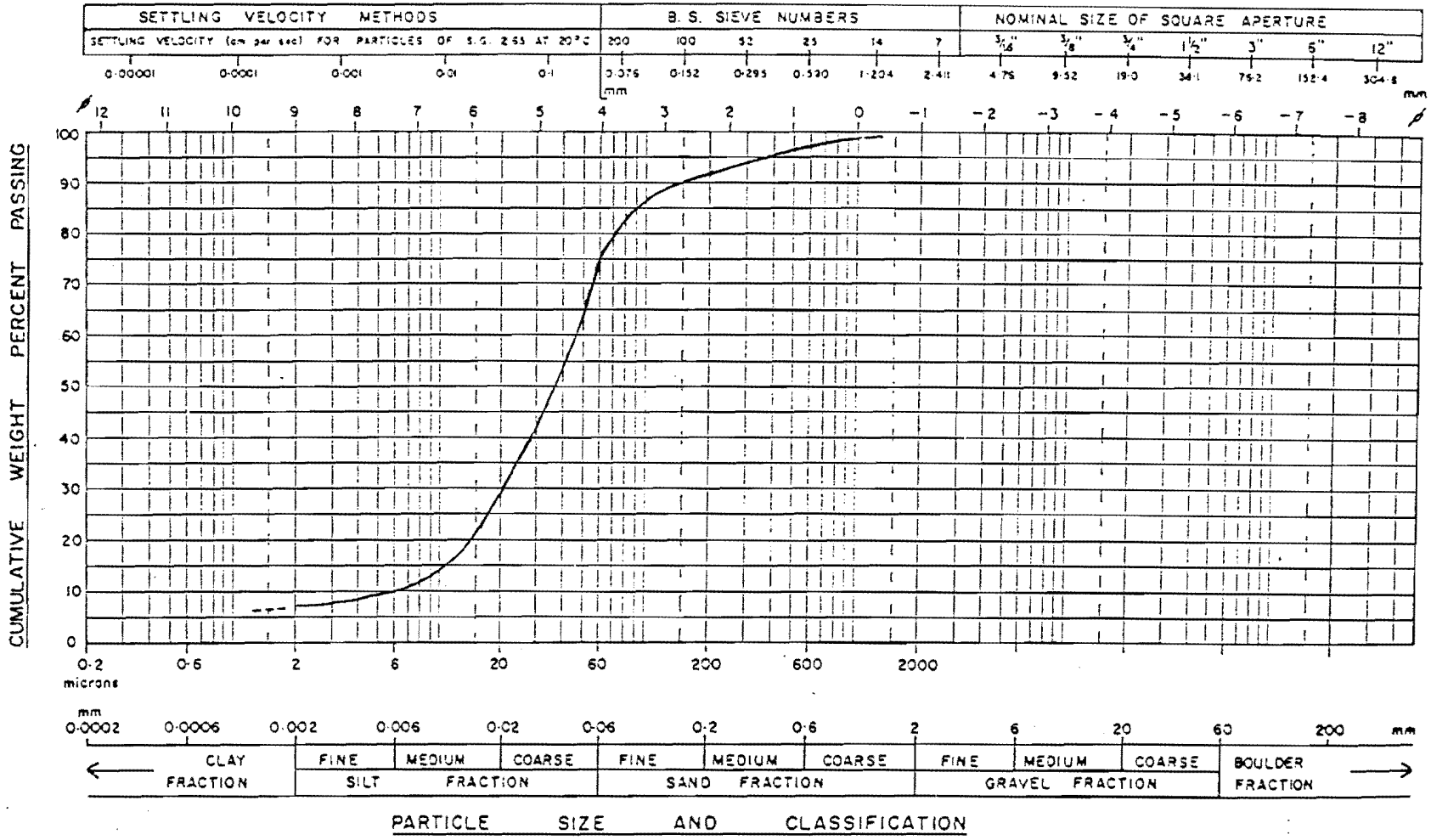
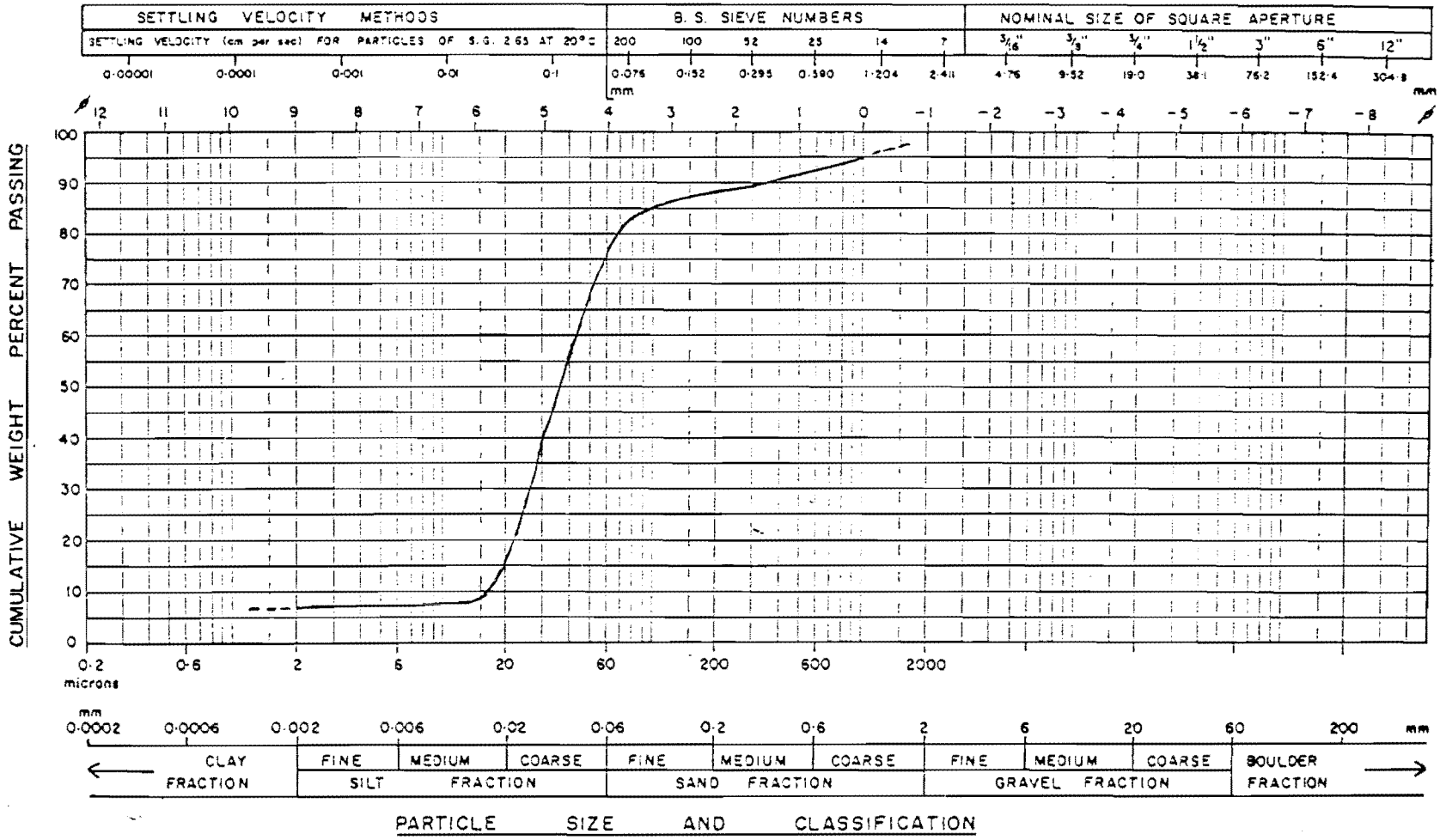


Figure A3.10 Grainsize distribution curve for 2% hydrated lime treated sample

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT NHAKA TERRACE SUBDIVISION SAMPLE NO 4% HYDRATED LIME SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION .... PORT HILLS ..... DATE ..... DATE .....



PARTICLE SIZE AND CLASSIFICATION

Figure A3.11 Grainsize distribution curve for 4% hydrated lime treated sample

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WHAKA TERRACE SUBDIVISION SAMPLE NO 2% CEMENT ..... SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION ..... PORT HILLS ..... DATE ..... DATE .....

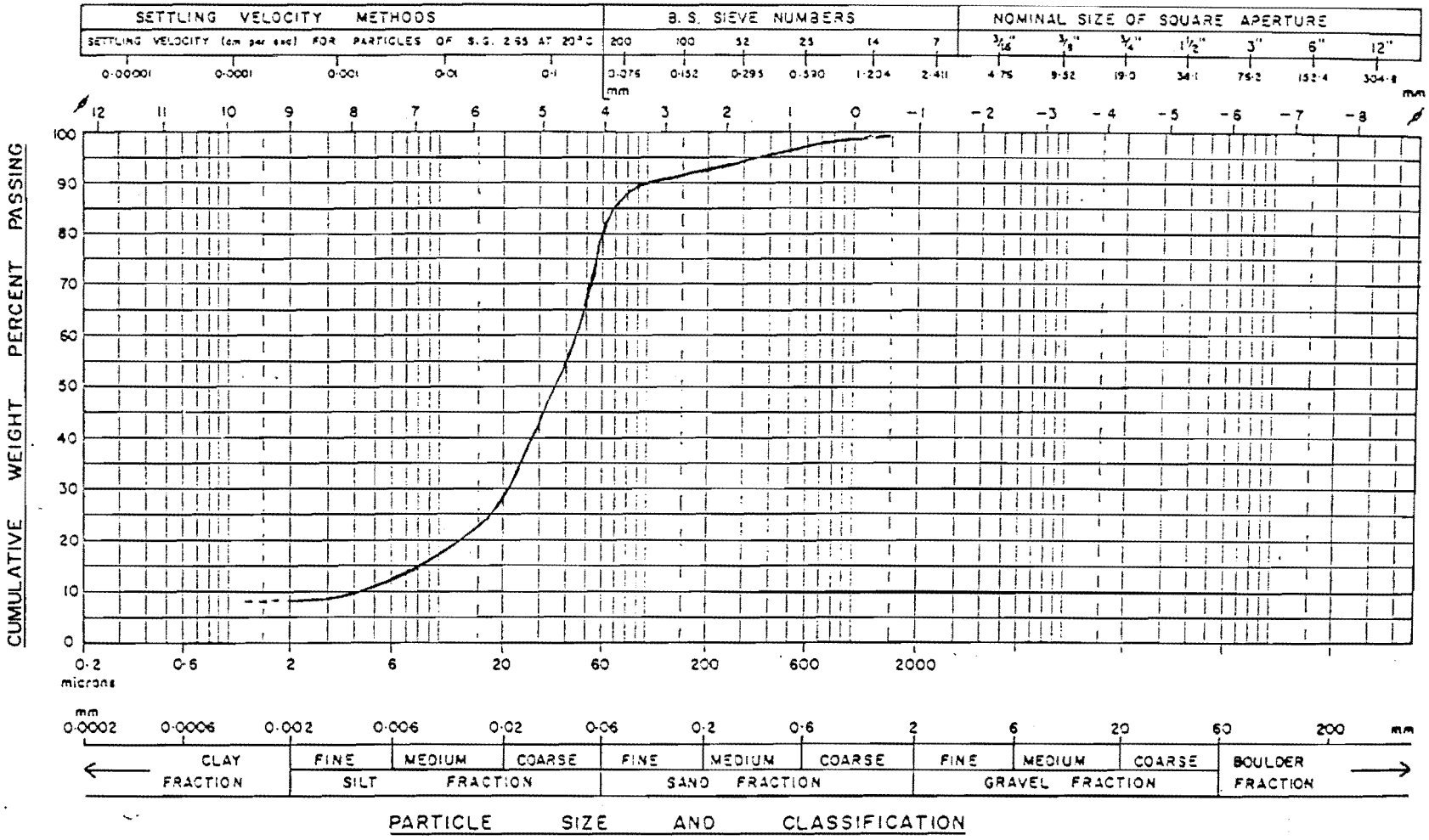


Figure A3.12 Grainsize distribution curve for 2% cement treated sample

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WHAKA TERRACE SUBDIVISION SAMPLE NO 4% CEMENT ..... SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION ..... PORT HILLS ..... DATE ..... DATE .....

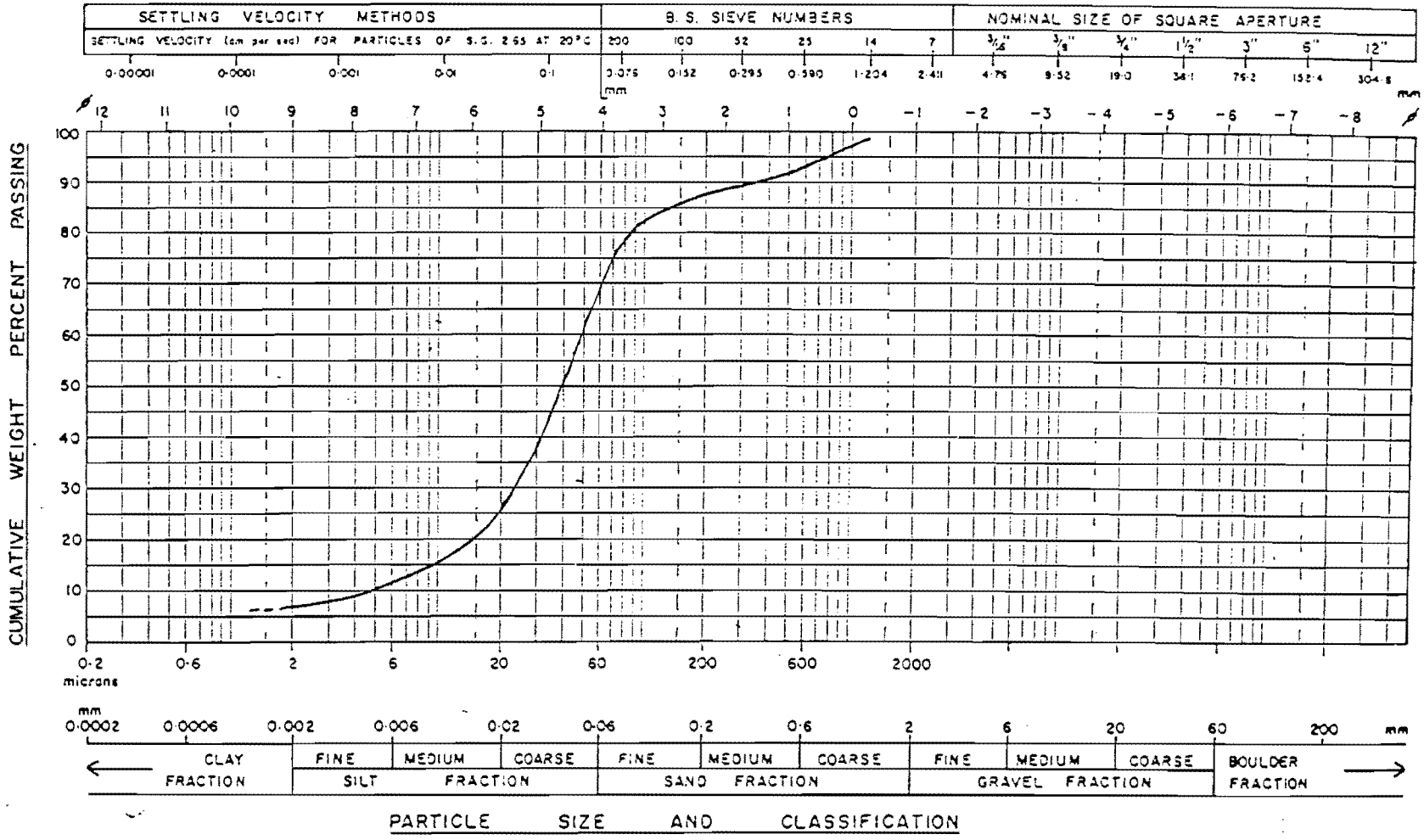


Figure A3.13 Grainsize distribution for 4% cement treated sample

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WHAKA TERRACE SUBDIVISION SAMPLE NO 2% GYPSUM & HYDRATED LIME SAMPLED BY ..... ANALYSED BY SIEVE AND HYDROMETER

..... LOCATION ...PORT HILLS..... DATE ..... DATE .....

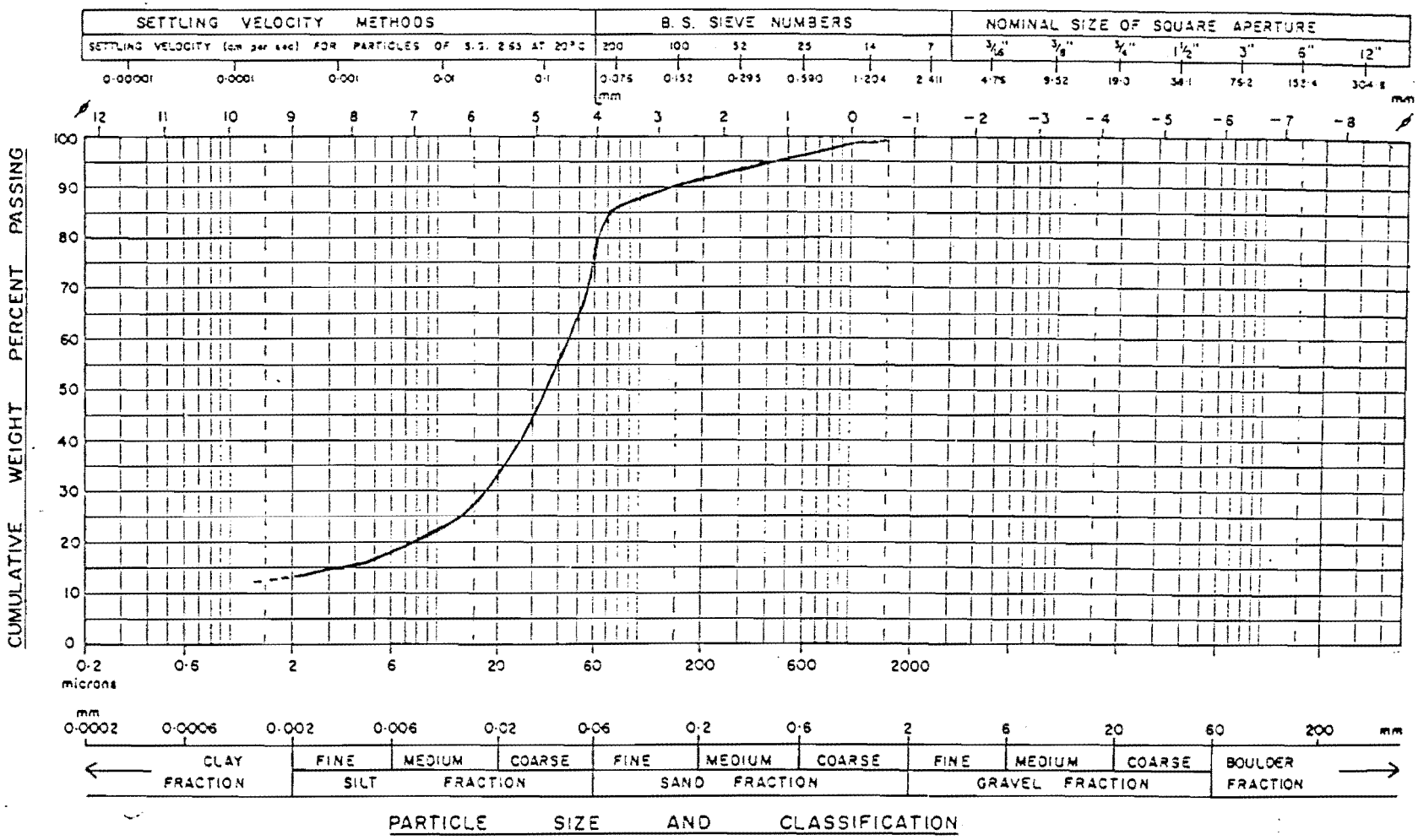


Figure A3.14 Grainsize distribution for 2% (gypsum& hydrated lime) sample

PARTICLE SIZE DISTRIBUTION — SEMI LOG PLOT

PROJECT WAIKATERRACE SUBDIVISION ... SAMPLE NO 4% GYPSUM & HYDRATED LIME SAMPLED BY ..... ANALYSED BY SIEVE & HYDROMETER

..... LOCATION ... PORT HILLS ..... DATE ..... DATE .....

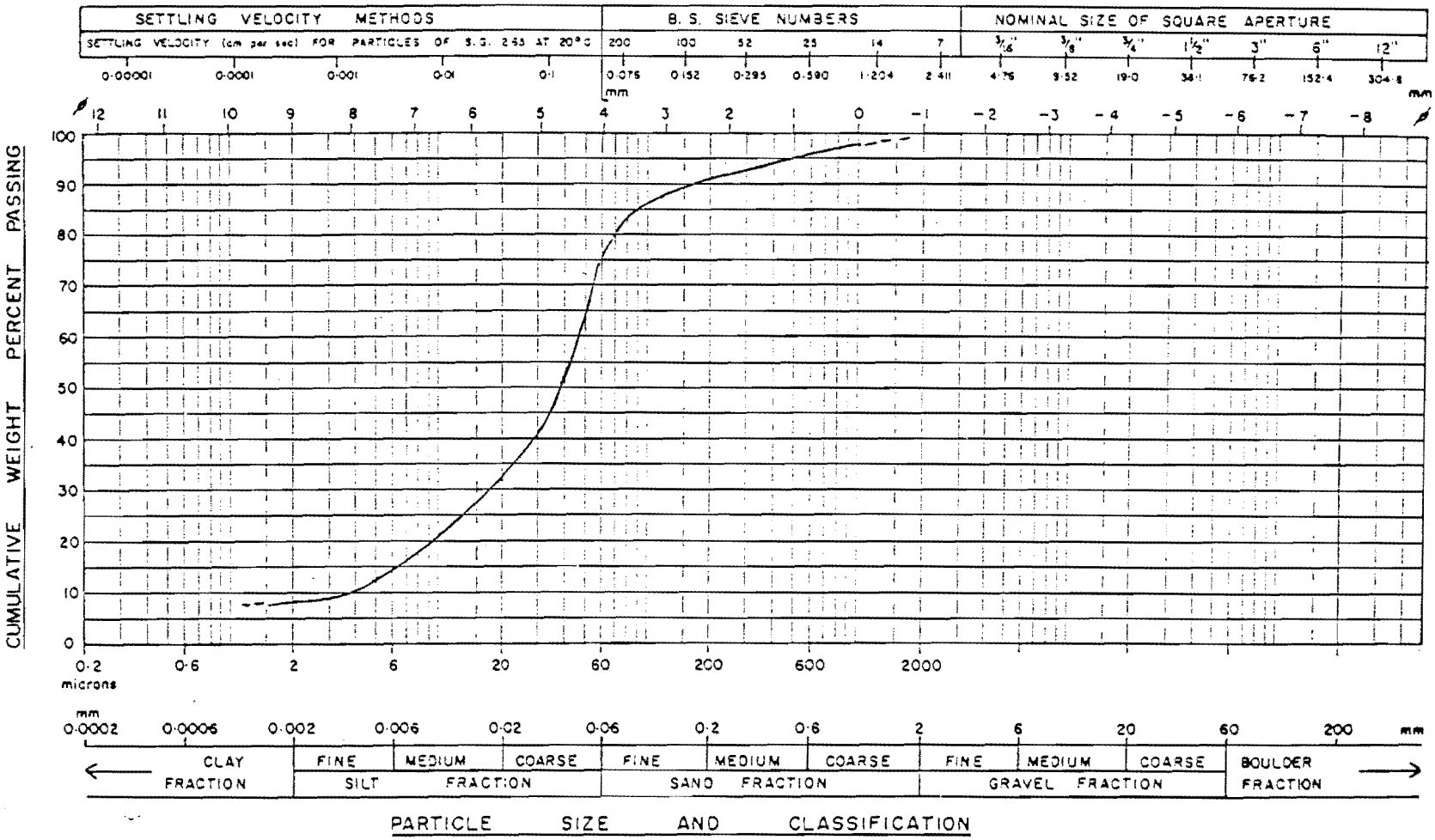


Figure A3.15 Grainsize distribution for 4% (gypsum & hydrated lime) sample

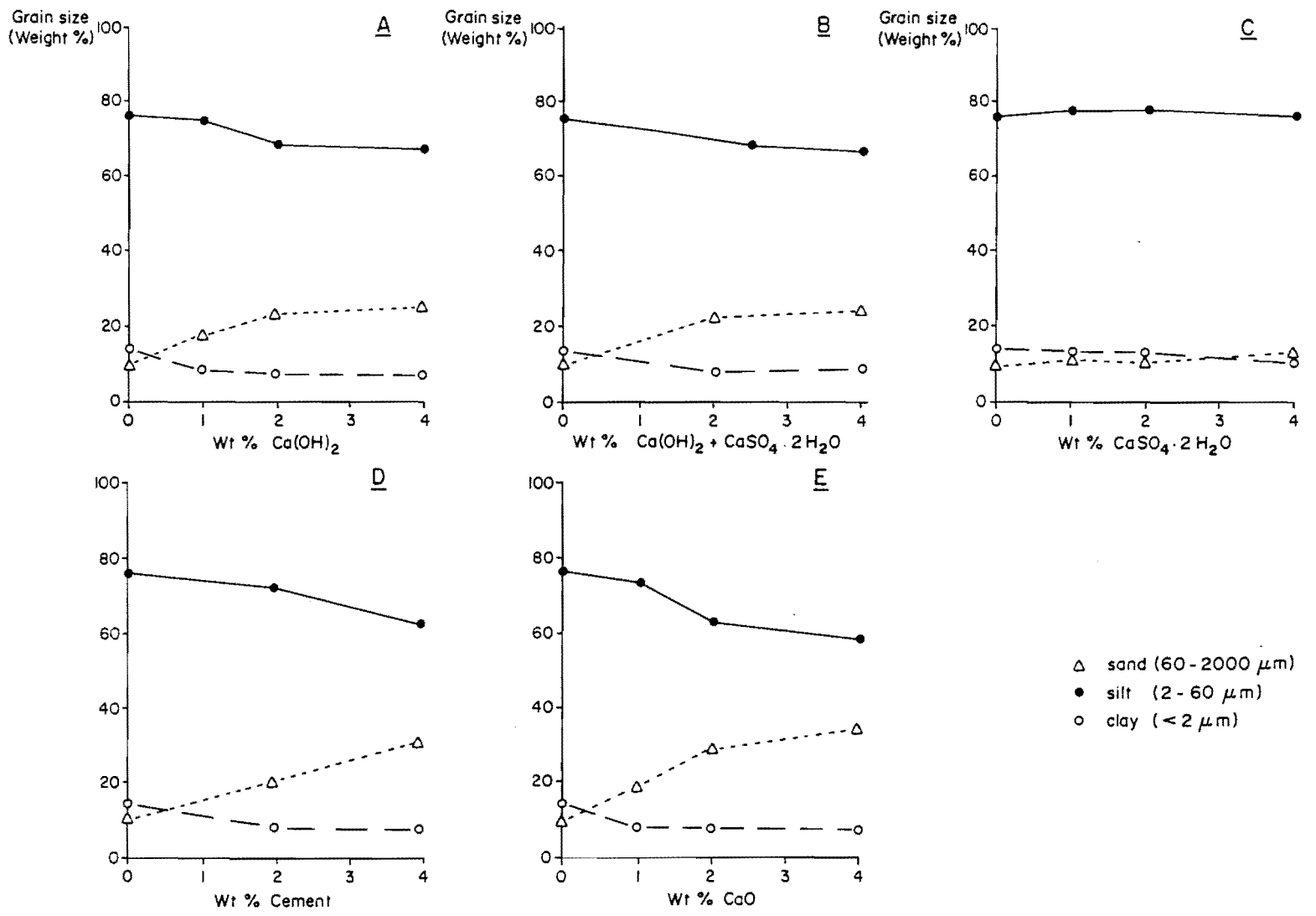


Figure A 3.16 Effect of stabiliser addition on grainsize distribution for A - hydrated lime, B - gypsum and hydrated lime, C - gypsum, D - cement, E - quicklime.

APPENDIX: 4 PERMEABILITY TEST

A4.1 Test Procedure

A4.2 Test Results

A4.1 Test Procedure

i) A bulk sample was compacted at OMC in a single layer (following N.Z. Standard 4402, part 2 (1981) test 14.) and a 35 mm tube sample was obtained from the mould, using a tube sampler.

ii) A portion of the tube sample was extruded and cured in the fog room at 20° C for 14 days. After curing the sample was placed into a permeability mould, (Fig 2.9) falling head sectional view).

iii) The sample and mould were then coated in melted wax making sure a rubber bung is placed over the bottom of the mould to prevent wax permeating into the sample. This process is repeated three to four times to ensure a water tight seal around the mould.

iv) The mould and sample were placed under vacuum for 40 minutes to desiccate the sample. The sample was subsequently left immersed in flowing water for 24 hours to achieve complete saturation.

v) At the start of testing the sample and mould are placed in a filled water basin and the water level in the stand pipe is recorded. The change in head per unit time is used to calculate the coefficient of permeability (k), according to the following formula.

$k = al/A \times \log_e . (H1/H2)/(T2-T1)$ where k= coefficient of permeability in mm/sec

d= The internal area of the standpipe in mm^2

l= The thickness of the specimen in mm

A= The area of the sample in mm^2

T1= Time start test

T2= Time stop test

H1= The initial height of the water in the stand pipe above the bottom of the sample in mm

H2= The final height of the water in the stand pipe above the bottom of the sample in mm

A4.2. Test Results

The permeability of field and stabilised samples are discussed in the chapter two section 2.5 and the data is summarised in table 2.4. The permeability for each stabilised sample is plotted against its compacted density and the results are shown in Fig A4.1

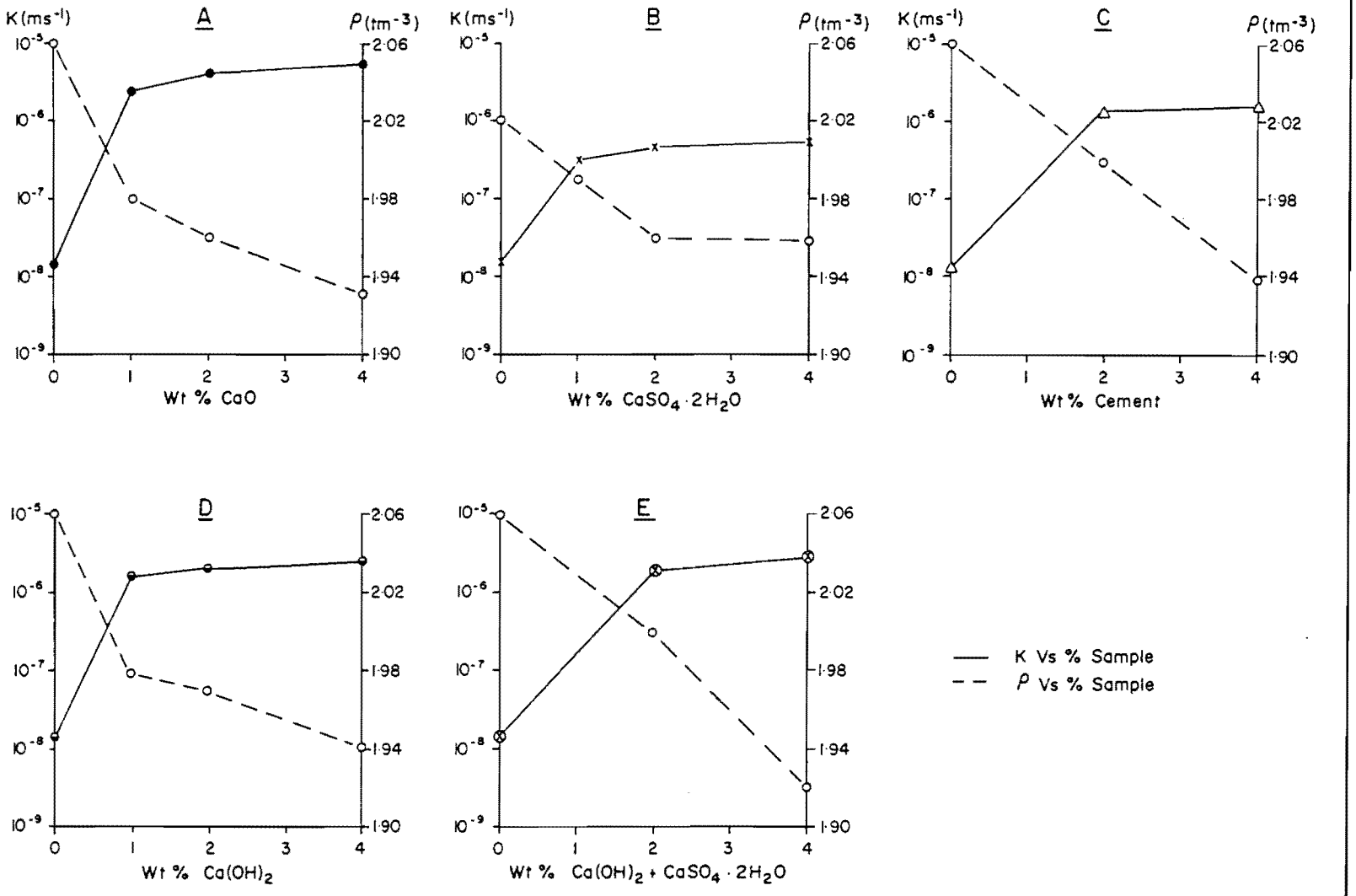


Figure A 4.1 Effect on permeability and compacted density of :- A - quicklime , B - gypsum , C - cement, D - hydrated lime, E - gypsum and hydrated lime.

APPENDIX: 5 EMERSON DISPERSION TEST

A5.1 Emerson Crumb Test

A5.2 Modified Emerson Crumb Test

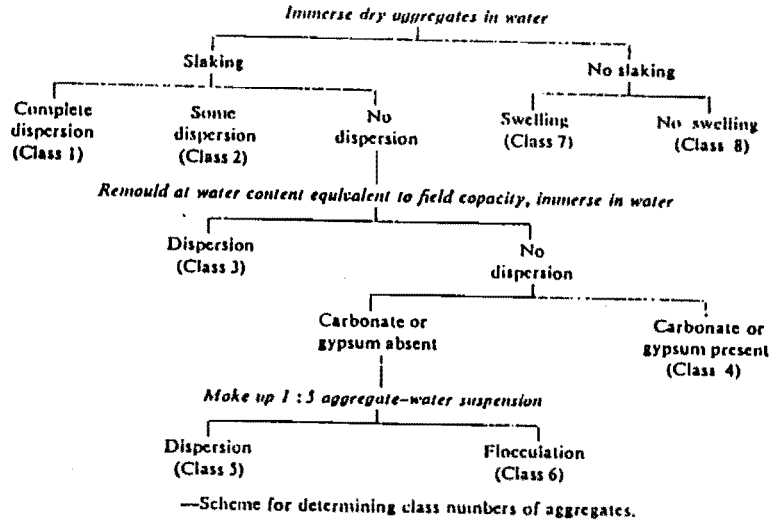
A5.1. Emerson Crumb Test

A5.1.1. Test Method

an air dried crumb of soil about 4-6 mm in diameter was dropped into a beaker filled with 50 cc of distilled water. The reaction between water and soil particles was then observed to determine the presence of swelling clays or dispersive behavior. The soil was then classified into the following classes;

A5.1.2. Classification

The test provides 8 classes which are shown in Fig A5.1



—Scheme for determining class numbers of aggregates.

Fig A5.1 Emerson Dispersion test Classification. (Emerson, 1967).

A5.2. Modified Emerson Crumb Test, (Sherard et al, 1976 b)

A5.2.1 Test Procedure

A crumb of untreated field sample (about 4-6 mm in diameter) at in-situ moisture content was dropped into a beaker of distilled water, and the extent of colloidal suspension of clay fraction was observed after 10 minutes, the sample was then classified according to the following scheme.

A5.2.2. Classification

Sherard dispersion classification includes:

Class 1 - No reaction: crumb may slake and run out on bottom of the beaker in flat pile but no sign of cloudy water caused by colloids in suspension.

Class 2 - Slight reaction: bare hint of cloud in water at the surface of the crumb.

Class 3 - Moderate reaction: easily recognizable cloud of colloids in suspension usually spreading out in thin streaks on bottom of beaker.

Class 4- Strong reaction: colloidal cloud covers nearly whole bottom of beaker, usually in a very thin layer. In extreme cases all the water in the beaker becomes cloudy.

APPENDIX : 6 PINHOLE ERODIBILITY TEST

A6.1 Test Procedure

A6.2 Yetton Classification

A6.3 Test Results

A6.1. Test Procedure

The samples for the pinhole erodibility test were obtained, 1) from the sample pit in the field and 2) from treated and untreated loess-colluvium bulk samples, which were recompacted in a single layer in proctor moulds, following N.Z. Standard 4402 part 2 test 14.

i) The tube samples were trimmed to a standard length of 50 mm, after which a 1 mm diameter hole was drilled through the center of the sample using a surgical needle.

ii) The sample was then set up in the apparatus, (figure A6.1) and water was passed through the sample under increasing heads of 50 mm, 180 mm, 380 mm and 1000 mm for 10 minute periods for each head respectively.

iii) The water discharge through the sample was collected in a volumetric cylinder, and the volume recorded at pre selected time intervals, along with observations of the colloidal content of the water, (Fig A6. 2-4).

iv) Sample classification was based on the measured flow rate under each head, plotted against the elapsed time, (Fig A6. 4.16).

Note: a) The test can be halted if sample failure occurs during the tests, (as suggested increase in flow rate and colloidal discharge).

b) To obtain the theoretical maximum discharge for each head the test equipment should be run without a sample.

A6.2. Yetton Classification

1) From the record of water volume over time the average flow rate in ml/sec is calculated for each minute period.

2) A graph is prepared with flow rate (Q) on the Y axis and time (minutes) on the X axis. Ten minutes periods indicating the head changes are indicated by vertical lines. The maximum flow rates possible without restriction by the sample are also shown by solid horizontal lines(Fig A6.5).

3) The data is plotted and the points connected by straight lines (Fig A6.4). Ignoring the first minute after each head change, the head at which "sustained erosion" first occurs over three or more minutes is noted. "Sustained erosion" is defined as that which produces a significant progressive increase in flow rate greater than 0.1 ml/sec over a three minute period.

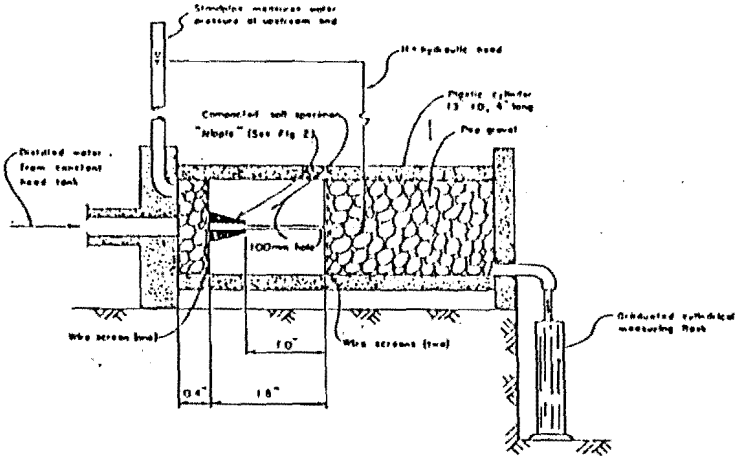
4) The head at which "sustained erosion" occurs, is subscripted as "E" while, non-erodible samples are classified as NE.

Note: a) If significant erosion first occurs at a low head, but only becomes sustained at the next higher head, then intermediate erosion classes can be adopted e.g. E 180-380.

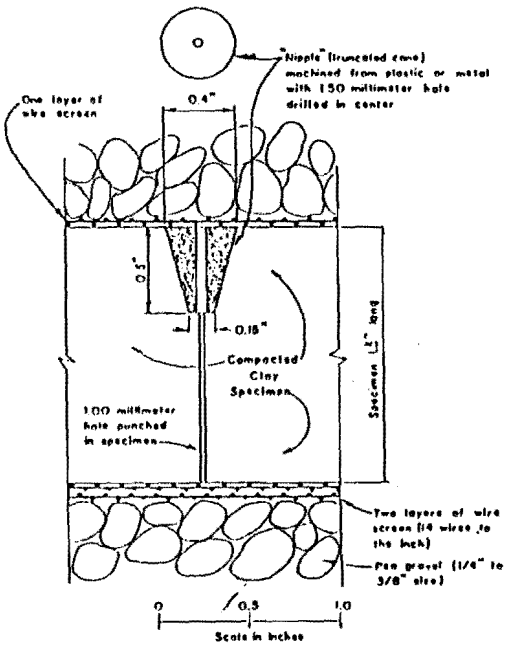
b) The maximum possible flow rate for each head without sample restriction is required to insure that any observed levelling off in increase in flow rate reflects sample characteristics and not the capacity of the equipment. This can be a particular problem in highly erodible material.

A6.3. Test Results

The results of the pinhole test are presented in table 2.6. while, the results are discussed in chapter two section 2.6.4. Fig A6.2-4 illustrates the raw data for some selected pinhole test and flow/time graphs stabilised samples are shown in Fig A6.5-17.



Pinhole Test Apparatus (1 in. = 25.4 mm)



Section through Pinhole Test Specimen (1 in. = 25.4 mm)

Figure A6.1 Pinhole erodibility test apparatus and section through test specimen. (from Sherard et al, 1976)

HEAD mm	TIME mins	FLOW Q ml	FLOW ml/sec	SEDMT. none	SEDMT. few	SEDMT. many	WATER dark	WATER pale	WATER misty	WATER clear	COMMENTS
50	00										Sample :
	01	25	0.4			*		*			0% stabiliser
	02	60	0.58			*		*			(after 14 days moist
	03	95	0.58			*		*			curing)
	05	169	0.61			*		*			
	07	245	0.63			*		*			
	00	285	0.66			*		*			
	09	327	0.7			*		*			
	10	371	0.73			*		*			
100	01	461	1.5			*	*				← Sample completely failed
	02	557	1.6			*	*				
	03										
	05										
	07										
	08										Erodibility class: E-180
	09										
	10										
300	01										
	02										
	03										
	05										
	07										
	08										inlet outlet
	09										
	10										
1000	01										
	02										
	03										
	05										
	07										
	08										
	09										
	10										Sample section after test

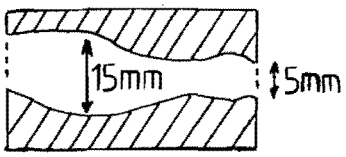


Figure A6.2 Pinhole erodibility test sheet for untreaded sample.

HEAD mm	TIME mins	FLOW Q ml	FLOW ml/sec	SEDMT. none	SEDMT. few	SEDMT. many	WATER dark	WATER pale	WATER misty	WATER clear	COMMENTS
50	00	25	0.4			*	*	*			Sample :
	01	43			*				*		1% gypsum treated (after 14 days moist curing)
	02	81	0.63	*					*		
	03	122	0.68	*					*		
	05	195	0.60	*						*	
	07	272	0.64		*					*	
	08	310	0.63		*					*	
	09	349	0.65		*					*	
	10	386	0.61	*						*	
180	01	457	1.18	*						*	
	02	535	1.3	*						*	
	03	618	1.38	*						*	
	05	783	1.37	*						*	
	07	948	1.37	*						*	Erodibility class:
	08	1032	1.4		*					*	E - 380
	09	1117	1.4		*					*	
	10	1198	1.35		*					*	
380	01	1305	1.78		*					*	
	02	1420	1.9		*					*	
	03	1550	2.16		*					*	
	05	1830				*			*		←sample completely failed and suite large number of silt size sediment is discharged
	07										
	08										
	09										
	10										
1000	01										inlet outlet
	02										
	03										10mm 4mm
	05										
	07										
	08										
	09										
	10										Sample Section after test

Figure A6.3 Erodibility test sheet for qypsum treated sample

HEAD mm	TIME mins	FLOW Q ml	FLOW ml/sec	SEDMT. none	SEDMT. few	SEDMT. many	WATER dark	WATER pale	WATER misty	WATER clear	COMMENTS
50	00		00								Sample :
	01	12	0.5		*				*		1% cao treaded
	02	45	0.55	*						*	(after 14 days moist
	03	77	0.53	*						*	curing)
	05	142	0.54	*						*	
	07	207	0.54	*						*	
	08	237	0.5	*						*	
	09	269	0.53	*						*	
	10	300	0.51	*						*	
100	01	355	0.91	*						*	
	02	478	1.05	*						*	
	03	478	1.0	*						*	
	05	602	1.03	*						*	Erodibility class: NE
	07	725	1.02	*						*	
	08	783	0.96	*						*	
	09	845	1.03	*						*	
	10	910	1.08	*						*	
300	01	995	1.41	*						*	
	02	1095	1.66	*						*	
	03	1190	1.58	*						*	
	05	1376	1.55	*						*	
	07	1570	1.61	*						*	inlet outlet
	08	1665	1.58	*						*	
	09	1762	1.61	*						*	
	10	1860	1.63	*						*	
1000	01	1995	2.25	*						*	
	02	2155	2.66	*						*	
	03	2315	2.66	*						*	
	05	2640	2.7	*						*	
	07	2960	2.66	*						*	
	08	3122	2.7	*						*	
	09	3280	2.63	*						*	
	10	3445	2.75	*						*	Sample section after test

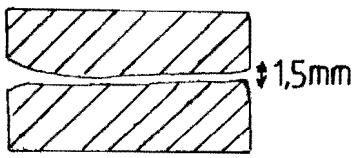


Figure A6.4 Erodibility test sheet for quicklime treated sample.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-D_6		MC	Gypsum 1%	E 360
WP3-D_7		AD	" "	E 50

NC Not cured, MC Moist cured, AD Air dried

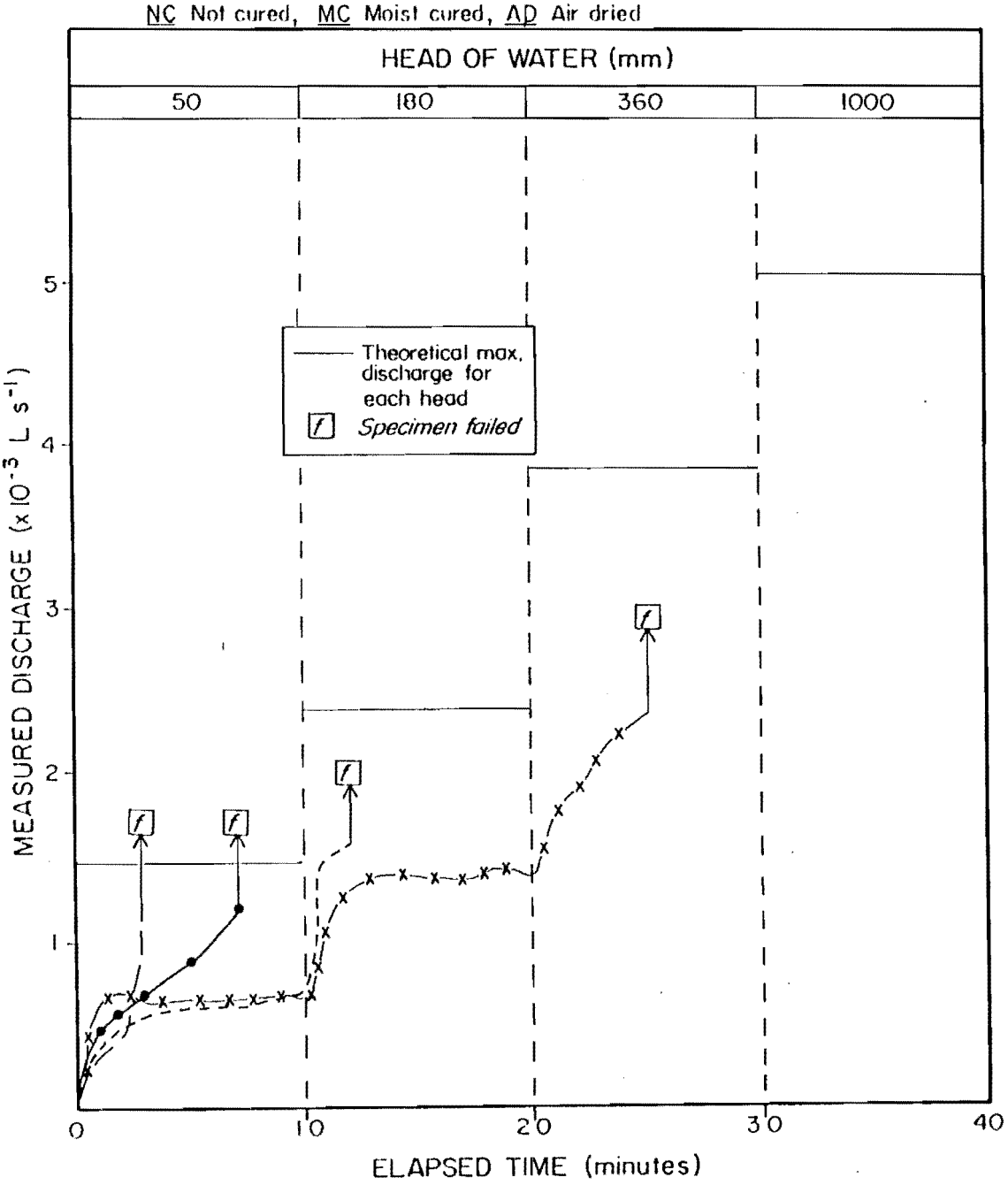


Figure A6.5 Erodibility of 1% gypsum treated samples

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-D_3		MC	Gypsum 2%	E 180
WP3-D_4		AD	" "	E 50

NC Not cured, MC Moist cured, AD Air dried

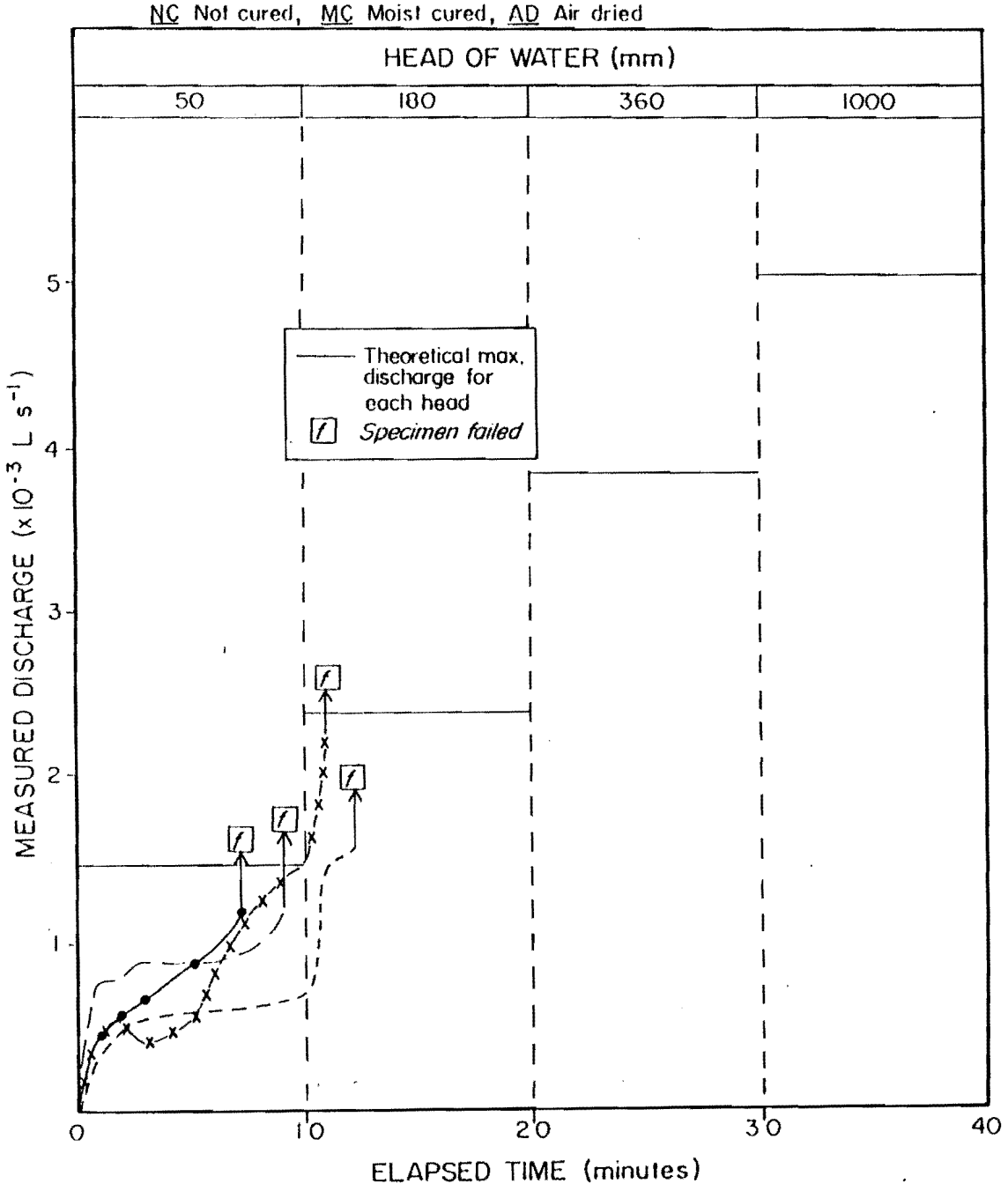


Figure A6.6 Erodibility of 2% gypsum teated samples.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-D		MC	Gypsum 4%	E1000
WP3-D_1		AD	" "	E180

NC Not cured, MC Moist cured, AD Air dried

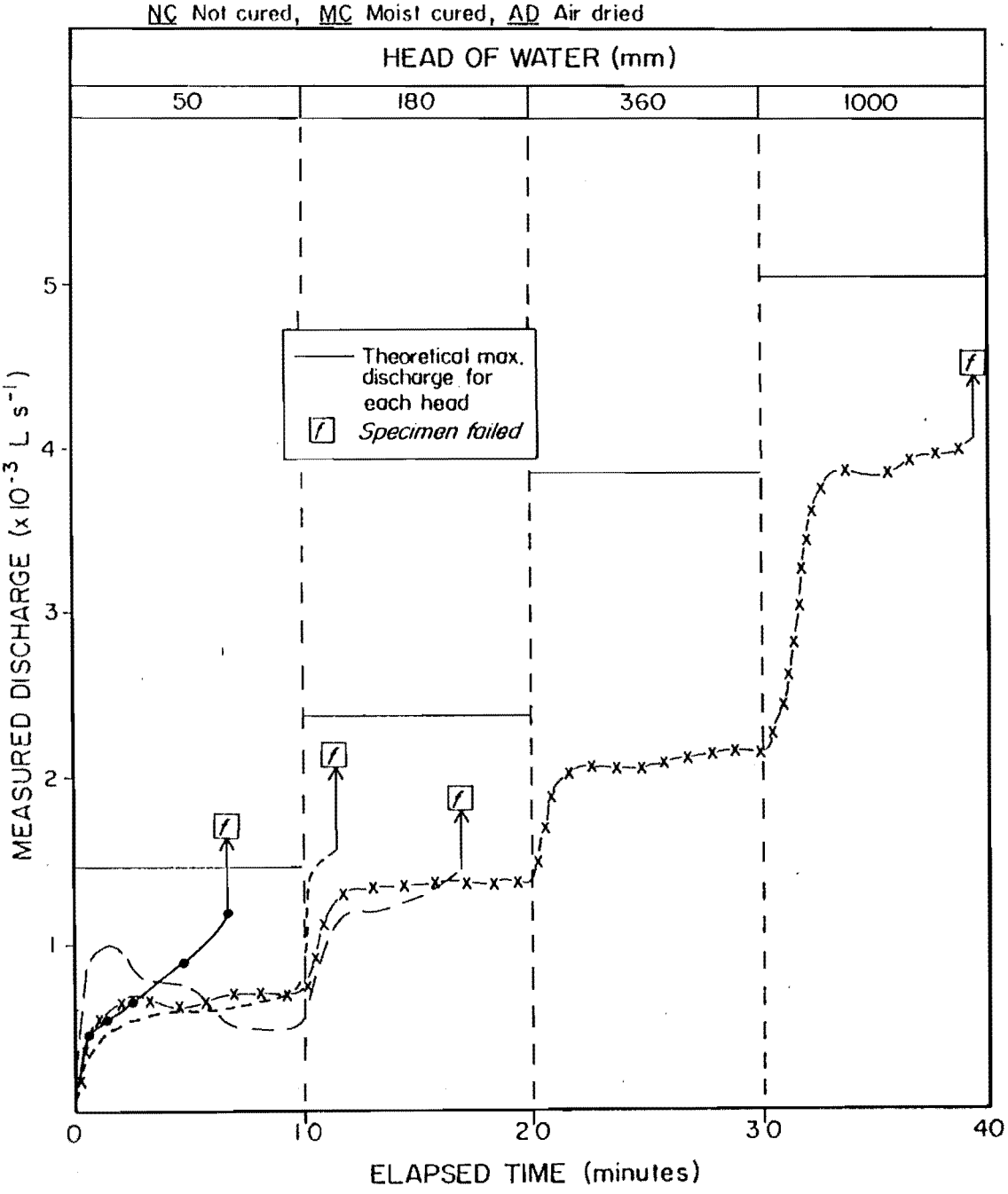


Figure A6.7 Erodibility of 4% gypsum treated samples.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-B_6		MC	Quicklime 1%	NE
WP3-B_7		AD	" "	NE

NC Not cured, MC Moist cured, AD Air dried

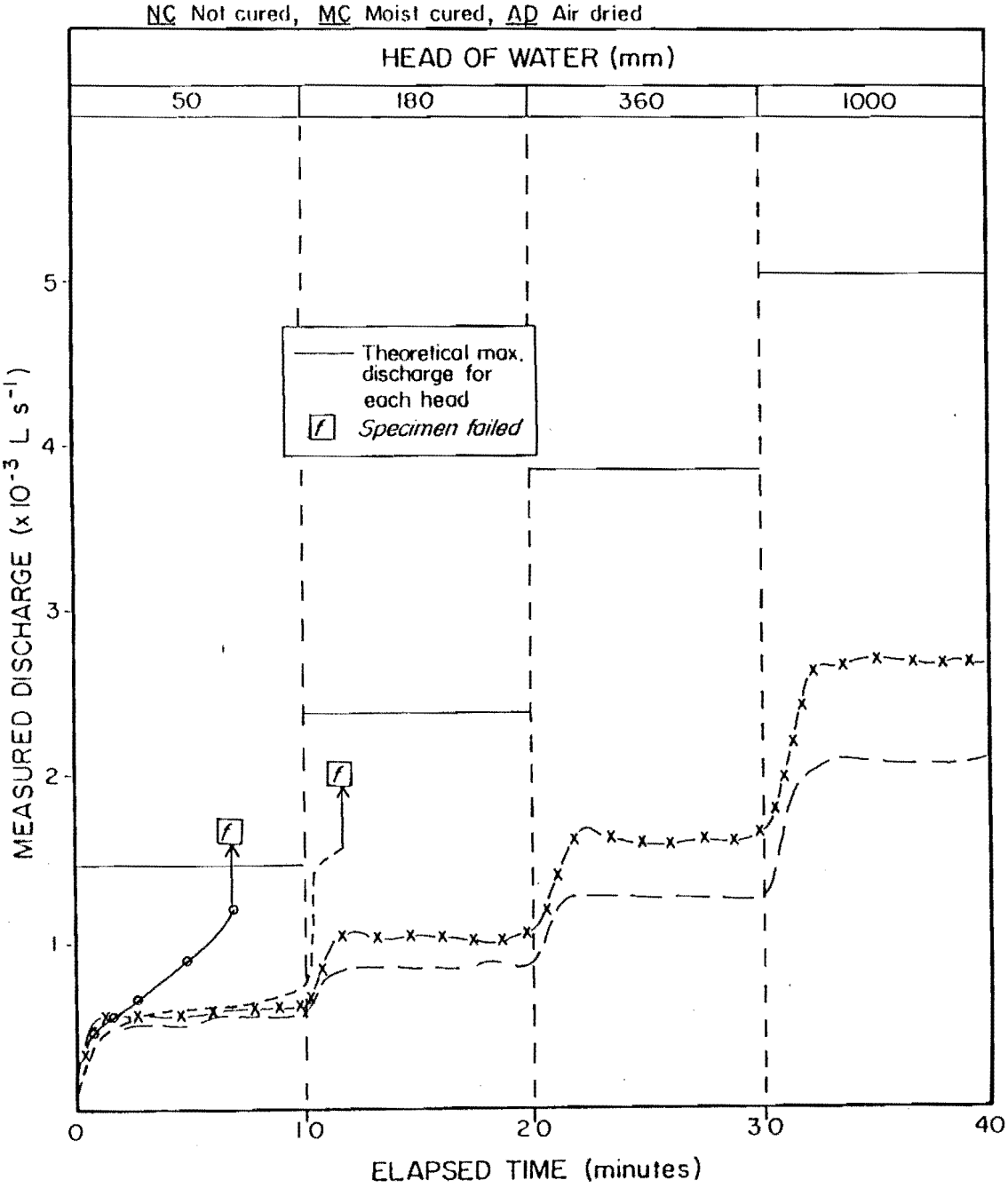


Figure A6.8 Erodibility of 1% quicklime treated samples.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-B_3		MC	Quicklime 2%	NE
WP3-B_4		AD	" "	NE
WP3-B_5		WD	" "	NE

NC Not cured, MC Moist cured, AD Air dried, WD Wetted and dried

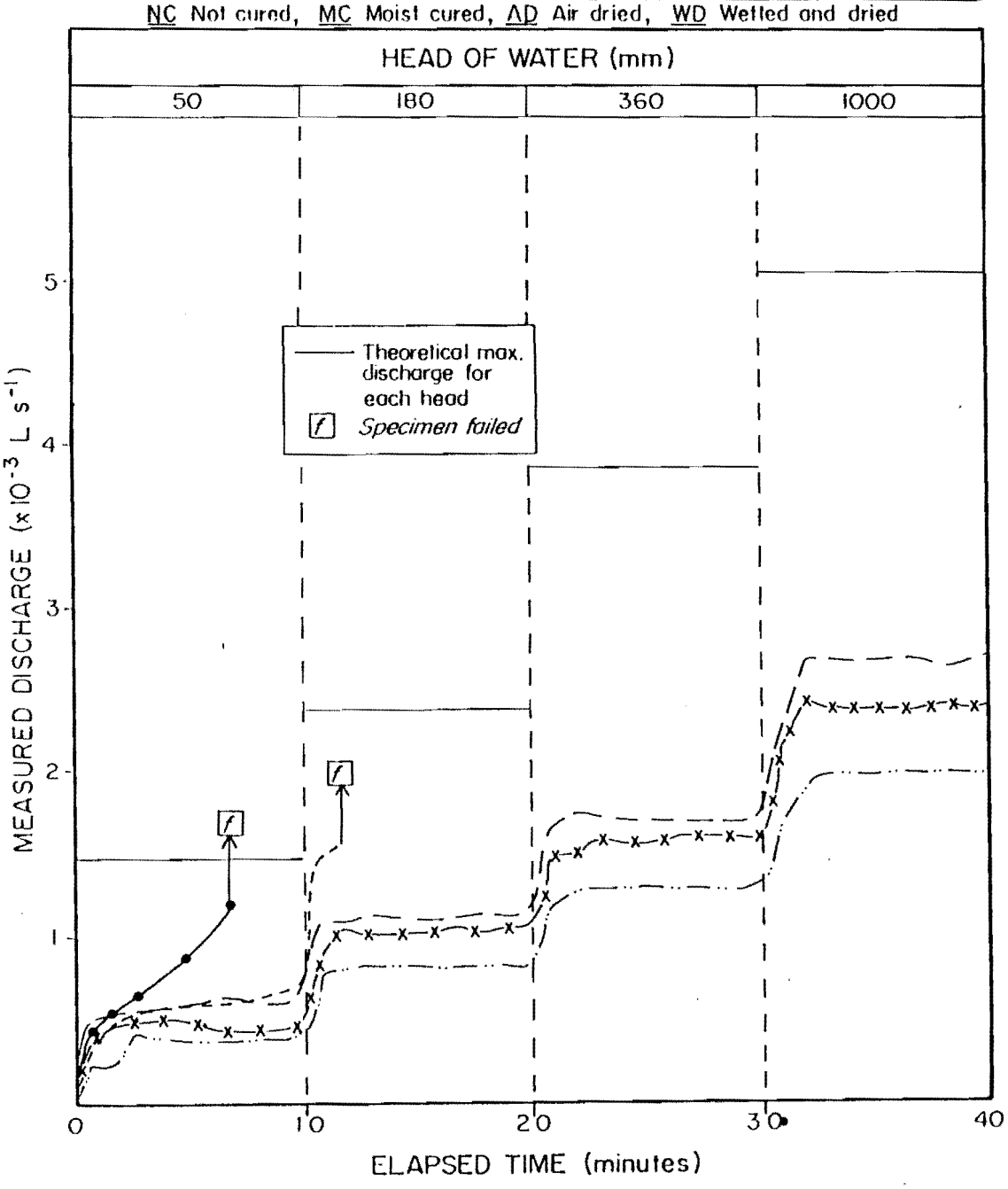


Figure A6.9 Erodibility of 2% quicklime treated samples.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-B		MC	Quicklime 4%	NE
WP3-B_1		AD	" "	NE
WP3-B_2		WD	" "	NE

NC Not cured, MC Moist cured, AD Air dried, WD Wetted and dried

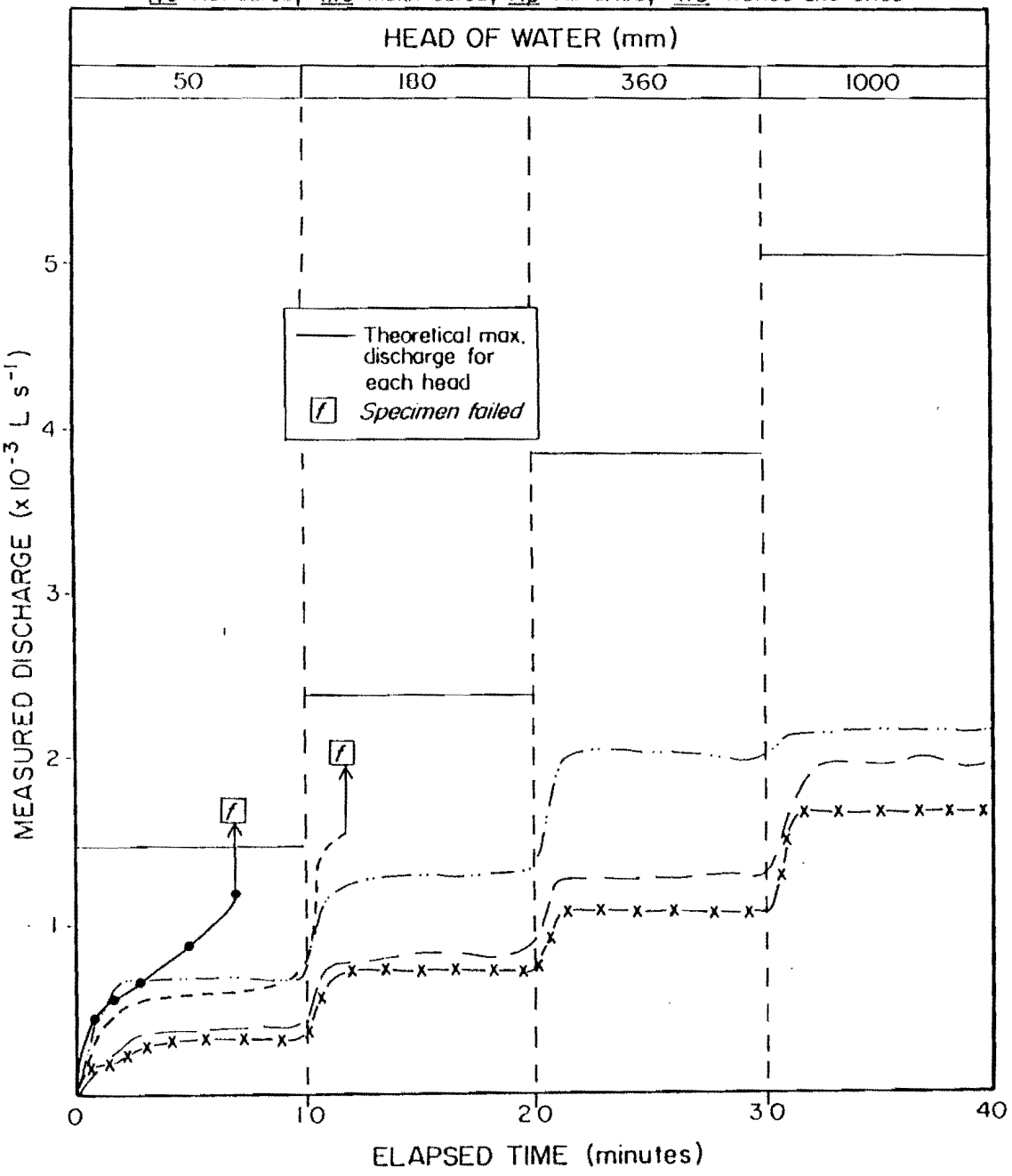


Figure A6.10 Erodibility of 4% quicklime treated samples.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-C_6		MC	Hydrated Lime 1%	NE
WP3-C_7		AD	" "	NE

NC Not cured, MC Moist cured, AD Air dried

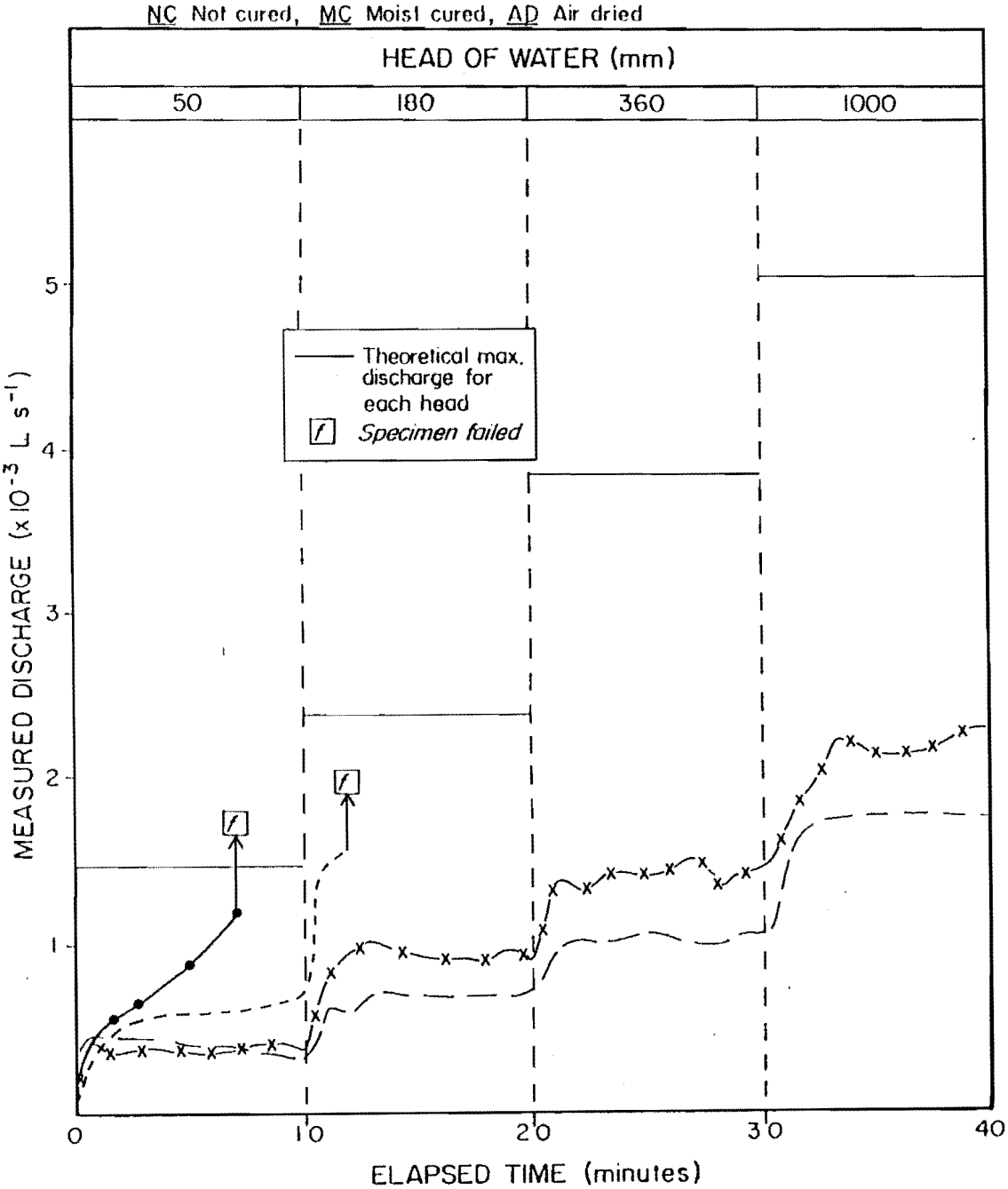


Figure A6.11 Erodibility of 1% hydrated lime treated samples.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-C_3		MC	Hydrated Lime 2 %	NE
WP3-C_4		AD	" "	NE
WP3-C_5		WD	" "	NE

NC Not cured, MC Moist cured, AD Air dried, WD Wetted and dried

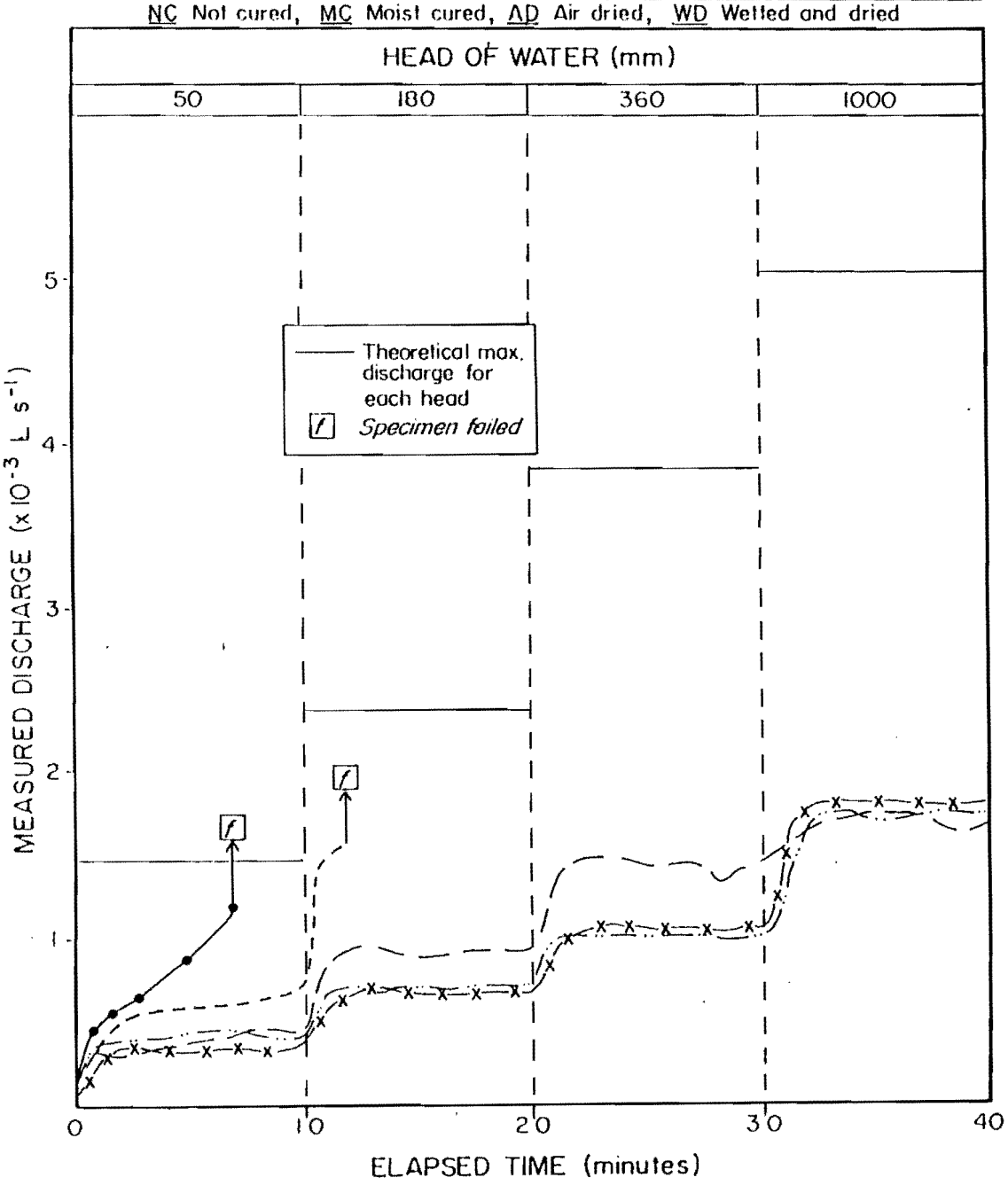


Figure A6.12 Erodibility of 2% hydrated lime treated samples.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-C		MC	Hydrated Lime 4 %	NE
WP3-C_1		AD	" "	NE
WP3-C_2		WD	" "	NE

NC Not cured, MC Moist cured, AD Air dried, WD Wetted and dried

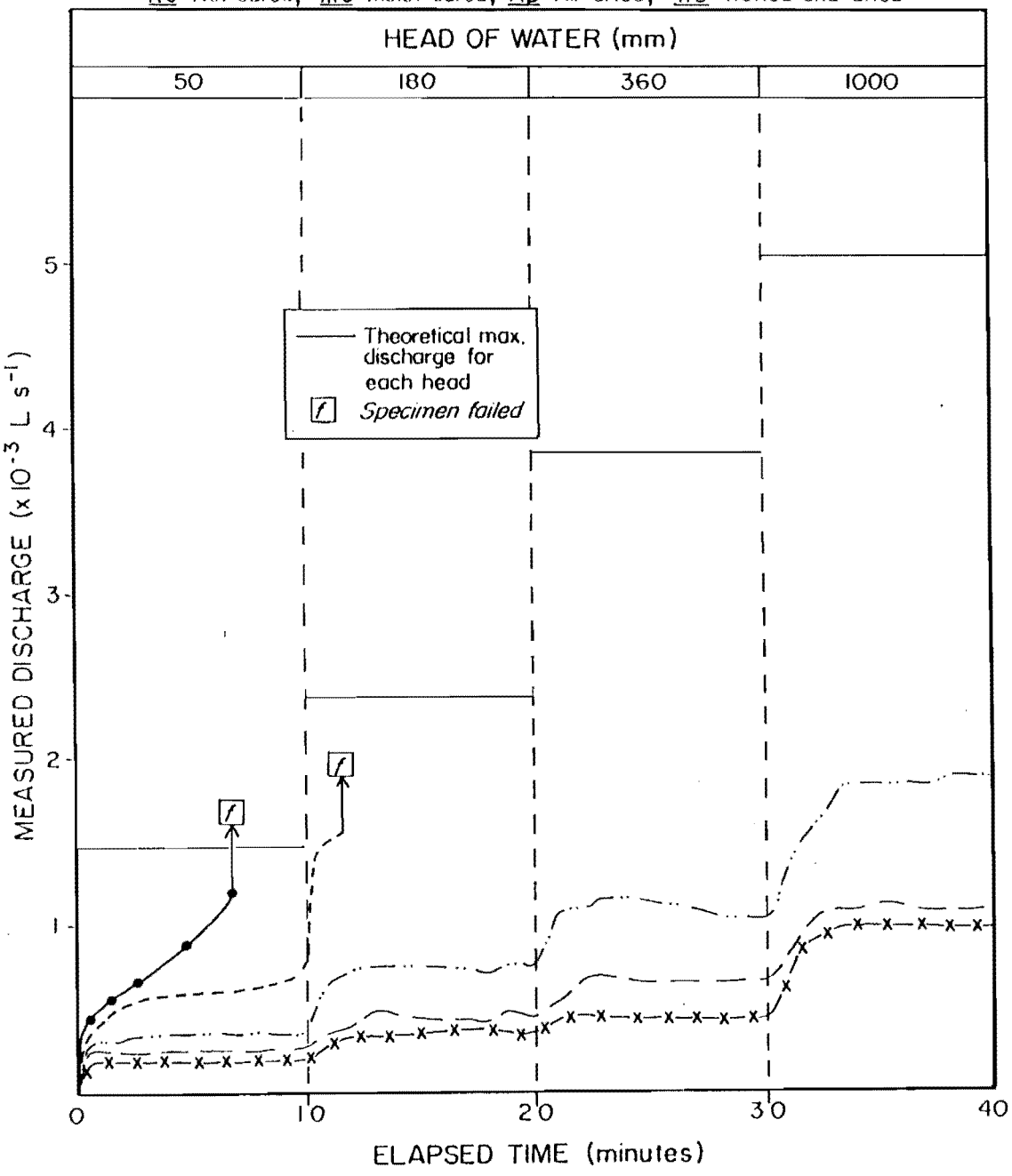


Figure A6.13 Erodibility of 4% hydrated lime treated samples.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-F_3		MC	Cement 2%	NE
WP3-F_4		AD	" "	NE

NC Not cured, MC Moist cured, AD Air dried

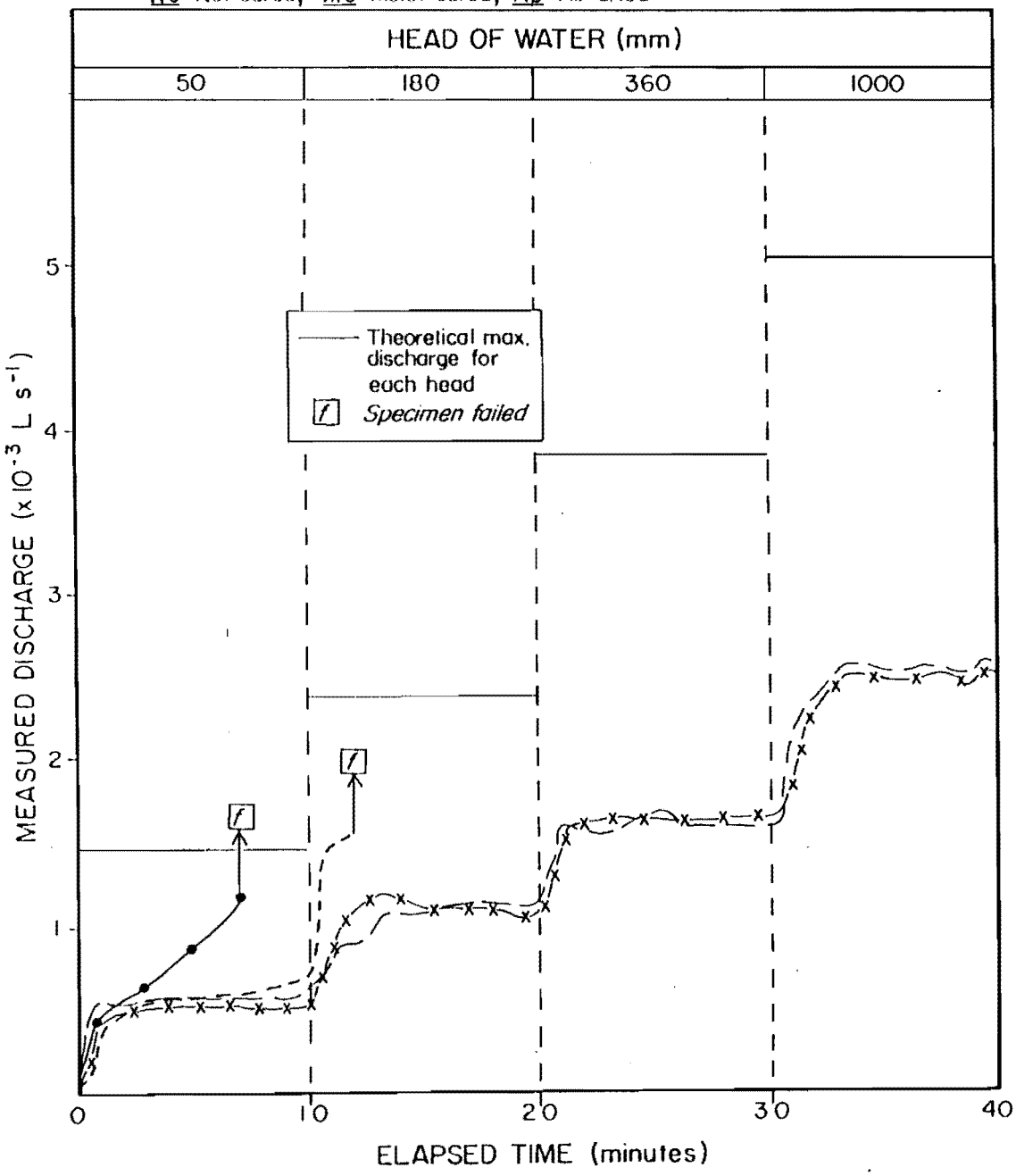


Figure A6.14 Erodibility of 2% cement treated samples.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-F		MC	Cement 4%	NE
WP3-F_1		AD	" "	NE
WP3-F_2		WD	" "	NE

NC Not cured, MC Moist cured, AD Air dried, WD Wetted and dried

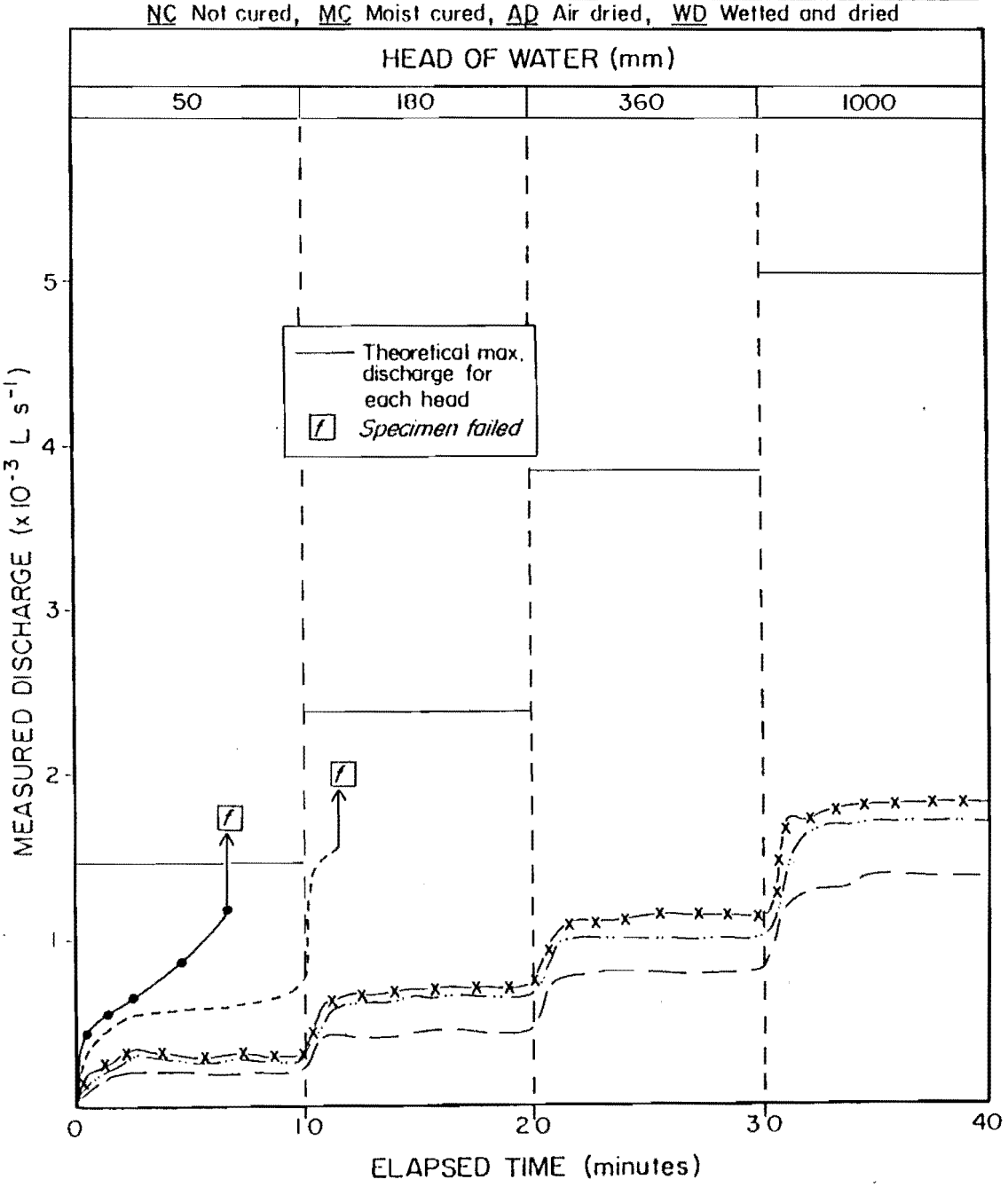


Figure A6. 15 Erodibility of cement treated samples.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-G_3		MC	(Gypsum & Hyd. Lime) 2%	NE
WP3-G_4		AD	" "	NE
WP3-G_5		WD	" "	NE

NC Not cured, MC Moist cured, AD Air dried, WD Wetted and dried

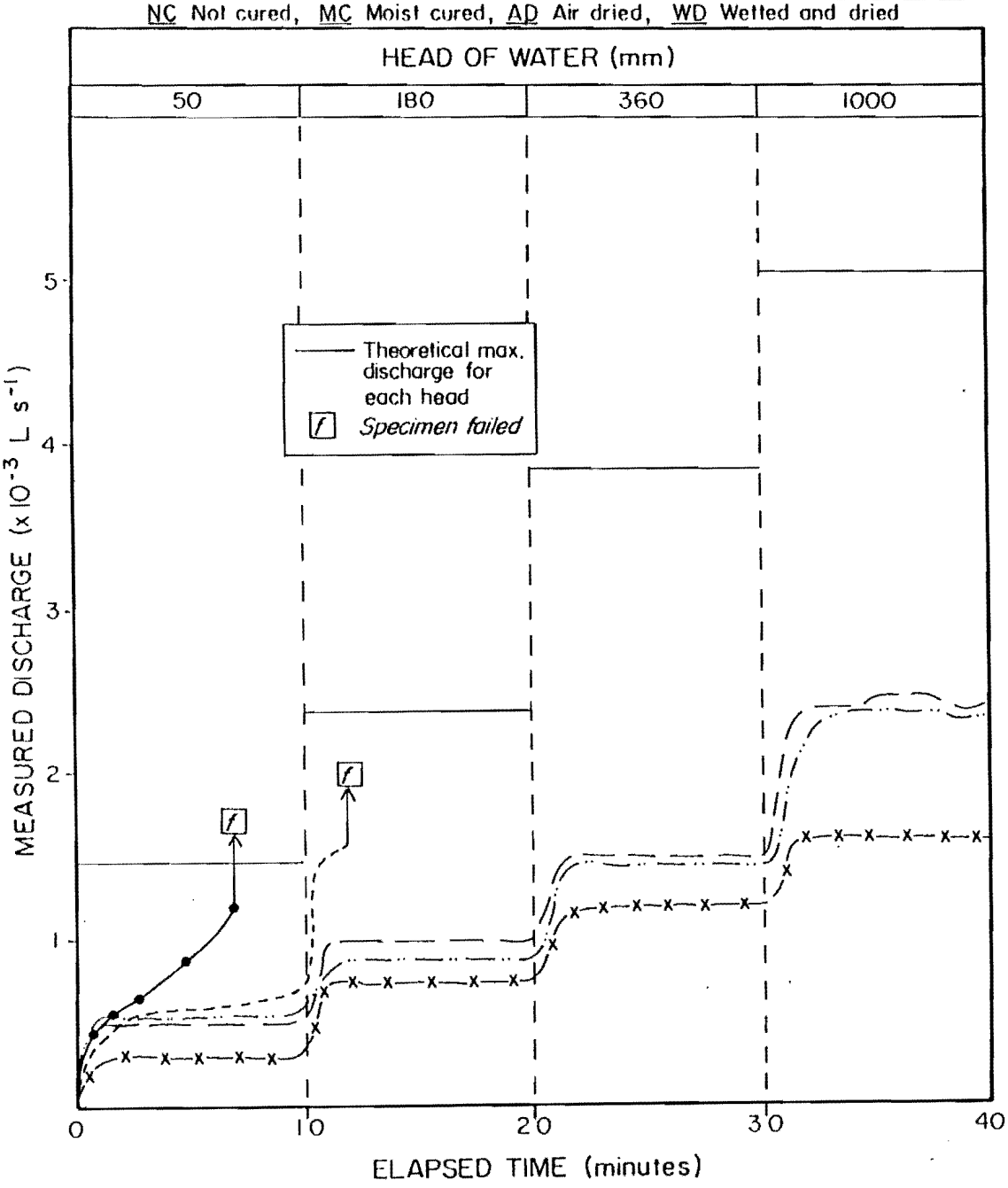


Figure A6.16 Erodibility of 2% (gypsum+hydrated lime) treated samples.

PINHOLE ERODIBILITY TEST (flow/time graph)

Sample No	Symbol	Curing Condition	Stabiliser	Erodibility Class
WP3-120-A		NC (in situ)	Non	E50
WP3-120-A_1		MC (recompacted)	Non	E180
WP3-G		MC	(Gypsum & Hyd. Lime) 4%	NE
WP3-G_1		AD	" "	NE
WP3-G_2		WD	" "	NE

NC Not cured, MC Moist cured, AD Air dried, WD Wetted and dried

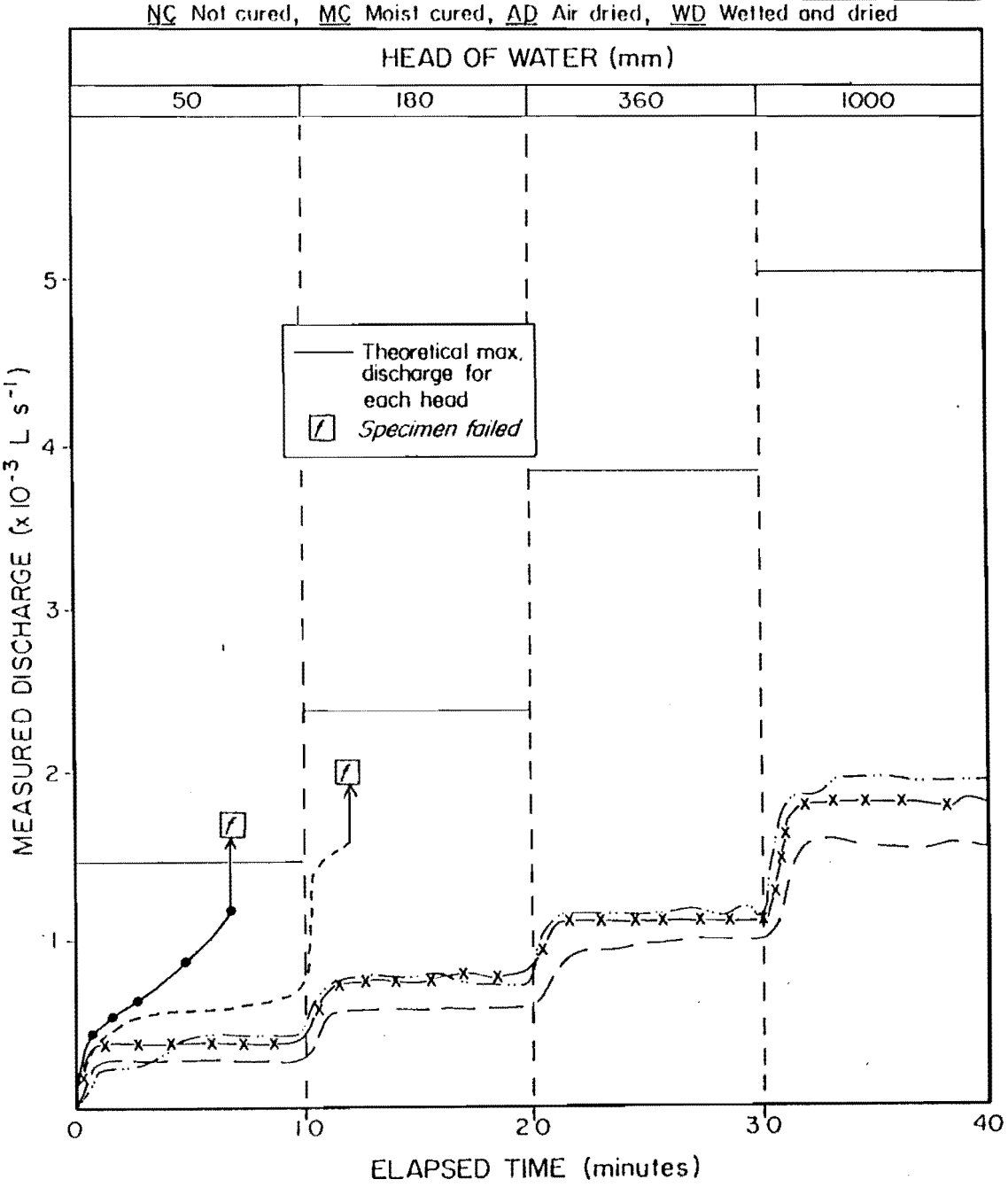


Figure A6.17 Erodibility of 4% (gypsum+hydrated lime) Treated samples.

APPENDIX: 7 SLAKING

Test Procedure

1) A bulk sample of untreated loess-colluvium soil was compacted at OMC according to N.Z. standard 4402 and moist cured for 14 days at 99% relative humidity at 20^{o} C.

2) Samples were weighted and placed in a plate designed to retain all material coarser than 2 mm. The plate and sample mould were placed in a jar and filled with tap water until the sample was completely immersed.

3) Samples were subjected to 5 cycles of 4 hours wetting and 20 hours of drying at room temperature. Samples were then classified on the basis of their behavior during immersion in water according to Worley Consultant Report (1984). These classes are present at table A7.1

4) After 5 cycles the samples were removed from the jar and remaining soil on top of the plate were weighed. The wet/dry slake index was calculated according to following formula.

$$W/D_{index} = 100 - (WL/Wo) \text{ where,}$$

Wl= weight lost Wo=original weight.

Table A7.1 Jar slake indices

SLAKING CLASS	DESCRIPTIVE BEHAVIOR
1	Degrades into a pile of flakes or mud.
2	Breaks rapidly and/or forms many chips.
3	Breaks rapidly and/or forms few chips.
4	Breaks slowly and/or forms several fractures.
5	Breaks slowly and/or develops few fractures.
6	No change.

APPENDIX: 8 UNIAXIAL SWELLING

A8.1 Background

The test was developed to measure the vertical expansion of soft rock samples from oven dried state to fully saturated condition. The test is out lined in ISRM (1981). However, some modification was adopted to determine swellability of in-situ and recompacted treated and untreated loess.

A8.2 Test Procedure

i) A bulk sample was recompacted at OMC in a single layer, following the N.Z. standard 4402, (part 2, 1981 test 14) after which a 35 mm tube sample was obtained from the mould, using a tube sampler.

ii) The sample is extruded from the tube and trimmed to the appropriate length, after which it is fitted into a stainless steel confining ring.

iii) The sample weight as well as its length and diameter is recorded for determination of its dry and bulk density. A sub sample is also taken for moisture content determination.

iv) The sample was then cured under the appropriate condition. After curing the sample is ready for testing; a porous stone and metal disc are placed over the top of the sample which was then placed in an empty water bath.

v) The transducer was placed on a metal disc and the plotter zeroed.

vi) The water bath was filled slowly with distilled water until the whole ring was covered with water. The swelling strain was then measured from LVDT/chart recorder, (Fig A8.1)

A8.3. Calculation

The uniaxial swelling strain (Es) is calculated by measuring the change in unit length of the sample according to the following formula.

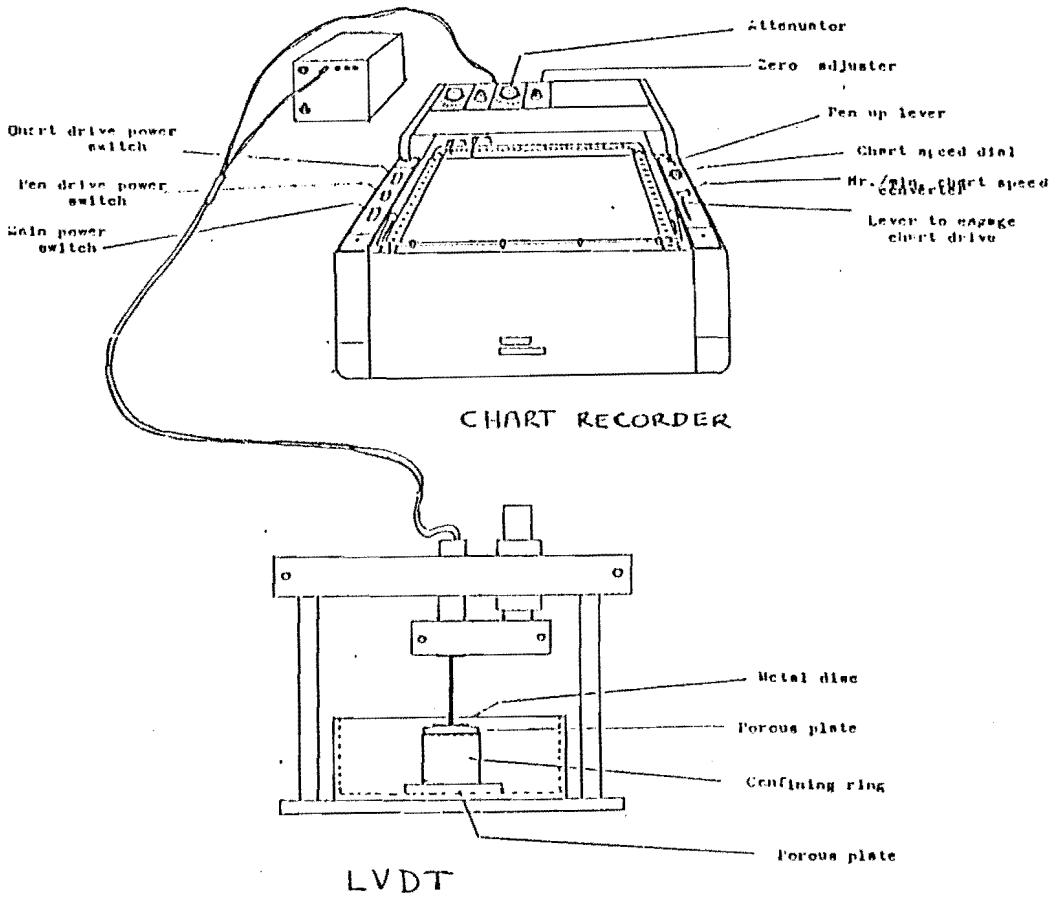
$E_S = dL/L \times 100\%$

where;

Es= swelling strain %

dL= change in length of sample, and

L= original length of sample



A8.1 Swelling Strain measuring apparatus.

A8.4. Results

The uniaxial swelling test results are illustrated in Fig 2.15 and data are summarised in table 2.8. For individual stabiliser the results are shown in Fig A8.2

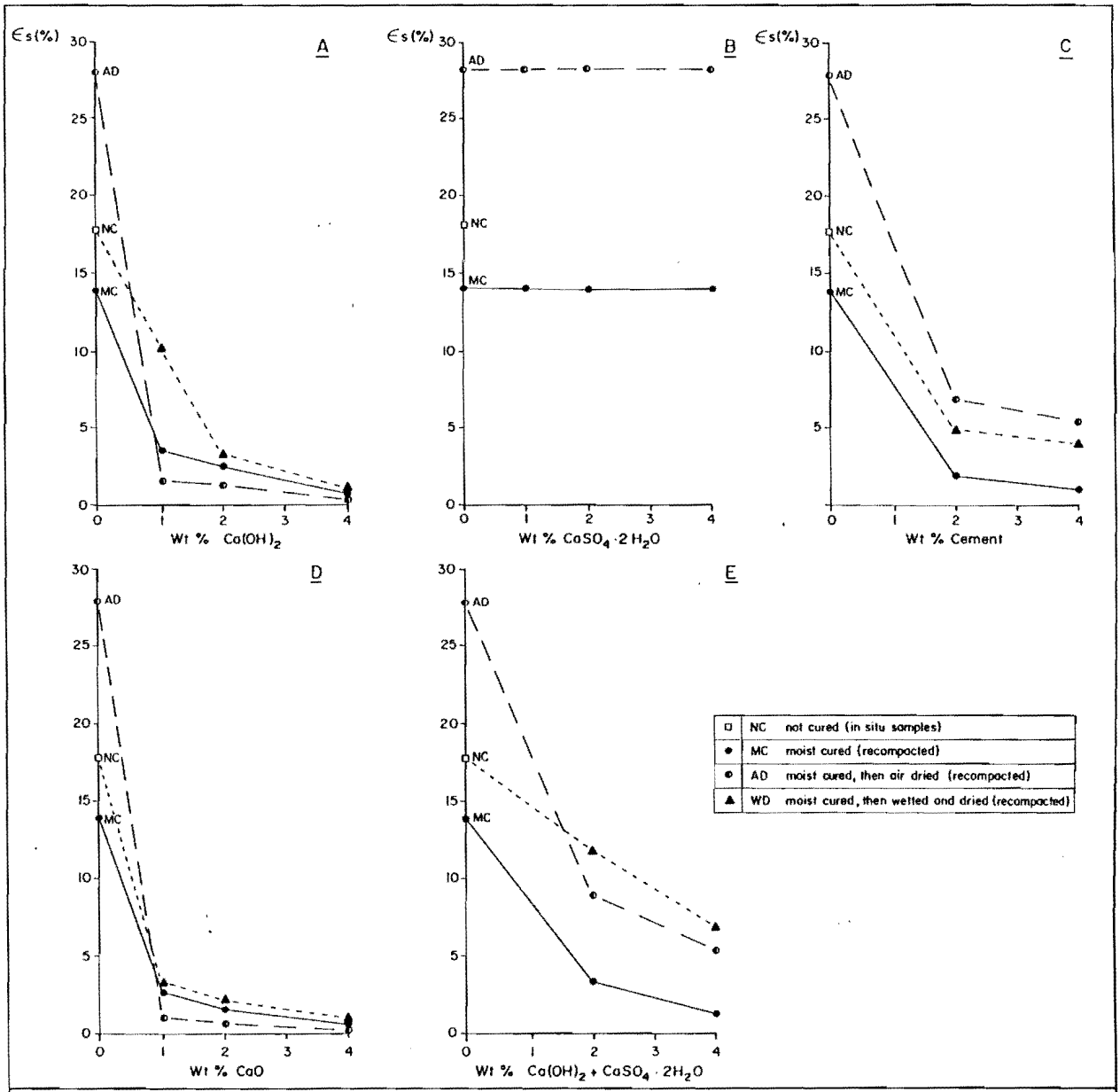


Figure A8.2 Uniaxial swelling strain of samples treated with: A. - hydrated lime, B - gypsum, C - cement, D - quicklime, E - gypsum and hydrated lime.

APPENDIX: 9 STRENGTH TESTS

A9.1 Unconfined Compressive Strength

A9.2 Sear Box Test

A9.1 Unconfined Compressive Strength Test

A Wykeham Farrance, 10000 kg stepless loading frame (Fig A9.1) was used to measure unconfined compressive strength of recompacted treated and untreated samples.

Test Procedure

Untreated and treated samples were compacted according to New Zealand Standard (1981) prior to testing.

Uncured moulds and 14 days moist cured moulds (at 99% RH and 20° C) of 115 mm length by 105 mm diameter were loaded at a rate of 0.5 mm per minute, until failure was observed.

Axial stress (kPa) was calculated from the normal force (kN) measured divided by the surface area of the sample. Axial strain is expressed as a percentage of change in length to the original length.

A9.2 Shear Box Test

The direct shear test on recompacted treated and untreated samples were carried out using a non reversing Wykeham Farrance shear box to determine the undrained peak shear strength parameters.

Test Procedure

Uncured samples and 14 days moist cured samples (at 99% relative humidity and 20°C) were compacted in a single layer into a 63 mm cylindrical shear box by a compaction machine using 15 blows, to produce moulds of 25 mm in length and 63 mm diameter with dry densities of 95% $\pm$2 of Max dry density. Samples were tested at four different normal loads (3.6 kN, 13.6 kN, 23.6 kN, and 33.6 kN) with a constant shearing rate of 1.2 mm/min. The peak shear stress values were plotted against the normal load to obtain the failure envelope, from which the cohesion and angle of internal friction were calculated.

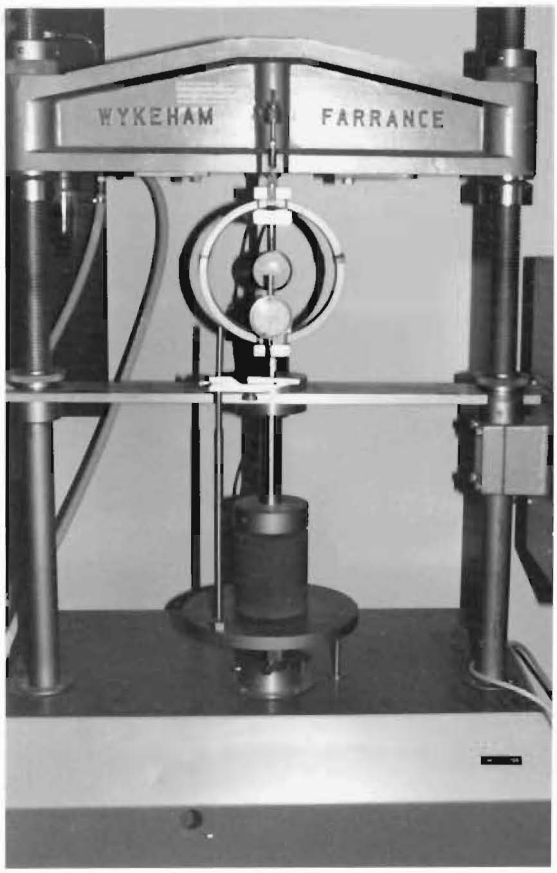


Fig. A9.1 The Wykeham- Farrance 10 000 kg stepless loading frame used to measure compressive strength.

APPENDIX: 10 SOIL CHEMICAL TESTS

A10.1 Determination of Organic Carbon Content
A10.2 Determination of Soluble Salt
A10.3 Determination of Cation Exchange Capacity
A10.4 Determination of Major Element
A10.5 Determination of $_{p}H$

A10.1 Determination of Organic Carbon Content

The concentration of organic carbon in loess-colluvium soil was measured using the titration method of Walkely and Black (1934).

A10.2 Determination of Soluble Salt

Analyses of total soluble salt concentration in pore water were carried out using the techniques of Metson (1956).

A10.3 Determination of Cation Exchange Capacity

The C.E.C of the leachate of the soil and exchangeable cations were measured using the method of Blakemore et al (1977).

A10.4 Determination of major elements

Major element analyses of Whaka Terrace loess-colluvium soil and chemical stabiliser agents were carried out using a Philip PW 1400 automatic spectrometer at the Geology Department of the University of Canterbury. Fusion beads were prepared following the methods of Norrish and Hutton, (1969)and the results were presented as percentage of element oxide.

A10.5 Determination of $_{p}H$

The $_{p}H$ value of untreated and treated loess-colluvium soil suspension is measured according to N.Z. Standard 4402, (1980) part 1, test 12(A) pp 75-77.

APPENDIX: 11 XRD ANALYSES

A11.1 Introduction

In this study samples were mixed with 4% concentration of chemical stabilisers (by weight of dry soil), and then moist cured for 14 days at 99% relative humidity and 20° C . The moisture content of samples was between 10-15% . Untreated samples were moist cured for the same period of time as stabilised samples.

A11.2 Sample Preparation

Preparation of natural and stabilised samples were carried out according to the following procedure.

a) Bulk Fraction

5 g of untreated and stabilised soil material were air dried and finely ground to pass through a 45 μm sieve. The soil fractions were then back-packed into Philips aluminum holders using the method of Hutchison (1974).

b) Clay Fraction

1) 25 g (dry weight) of material were hand dispersed in distilled water. The suspension was subsequently further dispersed using an ultrasonic probe at medium intensity for 3 minutes.

2) Samples were then wet sieved to obtain the mud fraction (<63 μm), which was subsequently transferred to a 1000 cc settling column. The sieve fraction still remaining was subjected to further cycles of wet sieving until all the mud fraction was obtained.

3) 25 cc of 2% sodium hexametaphosphate were added to the mud fraction in the settling column, which was then thoroughly stirred and left for observation.

If flocculation was observed the mud fraction was transferred to the centrifuge for further treatment. The sample was centrifuged at 2000 rpm for 10 minutes, after which the supernatant liquid was tipped off. The material was again rewashed with distilled water and thoroughly shaken before a further 10 minutes centrifuging. This process was continued until complete dispersion was observed by the cloudy appearance of the mud fraction in the sample tubes.

4) After complete dispersion is obtained the mud fraction is transferred back to the settling column, where a further 25 cc of 2% calgon was added. The column was subsequently topped up with distilled

water until the 1000 cc level, after which it was thoroughly stirred and left.

5) After 24 hours the suspension was syphoned off at a depth of 30 cm to obtain the clay fraction. The mud fraction left in the settling column was again topped up to the 1000 cc level, stirred and left for another 24 hours, after which the clay fraction was again syphoned off. This procedure was continued until the whole size range of the clay fraction was collected.

5) The clay fraction thus obtained was stored in a volumetric flask, and was subsequently flocculated out from the excess water using 20 cc of $MgSO_4$ (molar).

6) The concentrated clay fraction was subsequently centrifuged and washed with distilled water to remove the magnesium sulfate and redisperse the sample (according to the procedure of step 3).

7) The final step was to bring the dispersed clay suspension to a standard concentration. The suspension was transferred to a volumetric flask of 100 cc from which a 10 cc withdrawal was made. The 10 cc withdrawal was deposited into a beaker and weighted. The beaker plus suspension were subsequently placed under a heat lamp until the suspension was dry. The weight of the dry clay fraction was used to measure the concentration of clay per 10 cc of suspension. On the basis of this calculation the remaining 90 cc in the volumetric flask was further diluted or concentrated to achieve a suspension of 1% concentration of clay fraction.

8) The 1% suspension was thoroughly stirred, after which 2.25 cc was withdrawn and transferred onto a glass slide. Care was taken not to disturb the clay suspension while it was drying, and to keep it out of direct sunlight.

A11.3 Treatment Techniques

In this study various treatment techniques were used to identify the clay mineral suit present in the loess-colluvium bulk sample from Whaka Terrace. Analyses are based on the techniques of Thorez 1976. The treatment procedure is as follow;

a) Glycolation

The effect of glycolation on the basal spacing of clay minerals is given in Fig A11.1. Oriented mount of clay fraction were

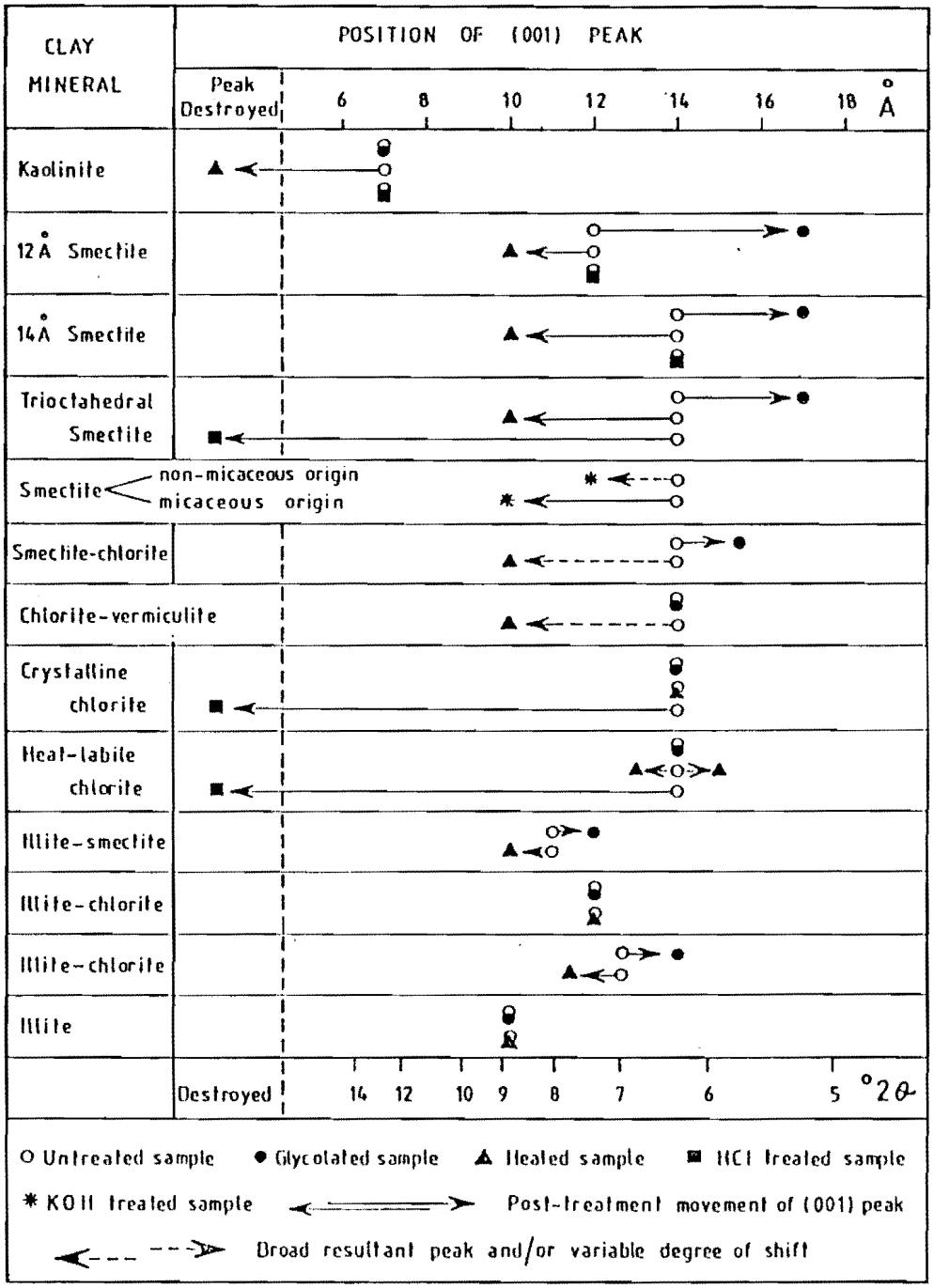


FIG.A11.1 Diagram illustrating the movement of (001) X-ray diffraction peaks when clay minerals are subject to various treatments: ethylene glycol saturation; heating at 500°C for 1 h; boiling for 5 min in 10% HCl; saturation in 1 N KOH for 15 h followed by 1 N KOH at 90°C for 1 h.

(from Hume & Nelson, 1982)

saturated by a concentration of 10% glycerol in water, using an atomiser to identify swelling clay (Fig A11.2).

b) Acid Treatment

HCl has been used to distinguish between 7 Å kaolinite (001) peak and 7 Å chlorite (002) peak.

The clay fraction of loess soil were boiled at 80-90° C with 10% HCl for 20 minutes. hydro chlorite acid dissolved the Chlorite, then remaining peak at 7 A° belongs to kaolinite (Fig A11.2).

c) Heat Treatment

Heating causes dehydration or destruction of crystal lattice of some clay mineral species. The identification techniques is given in Fig A11.1.

In this study the untreated mount of clay fraction were heated to 450° C and 550° C for period of 1 hour to distinguish kaolinite , Fe-chlorite and Mg Chlorite. The presence of Fe-chlorite in loess-colluvium from Whaka Terrace is shown in Figure A11.2.

A11.4 Semi-quantitative Calculation

a) Bulk Fraction

In this study the relative abundances of Quartz, Feldspar and clay mineral present in loess-colluvium were measured using Nelson and Cochrane (1970) techniques.

The height of specific peaks above background were measured (table 4.6) and the results were compare with standards to provide relative abundance of minerals present in the non-oriented powder sample. The standards is given in Figure A11.3.

b) Clay fraction

The relative abundances of illite (I), chlorite(C), chlorite-illite (C-I), kaolinite (K) and Undifferentiated mixed layer (UN) on the clay fraction of loess soil were calculated using the method of Hume and Nelson (1982), which is based on the following assumptions.

1) The reported clay minerals are considered to comprise 100% of the sample, whereas in some samples there are other minerals present, as well as amorphous minerals.

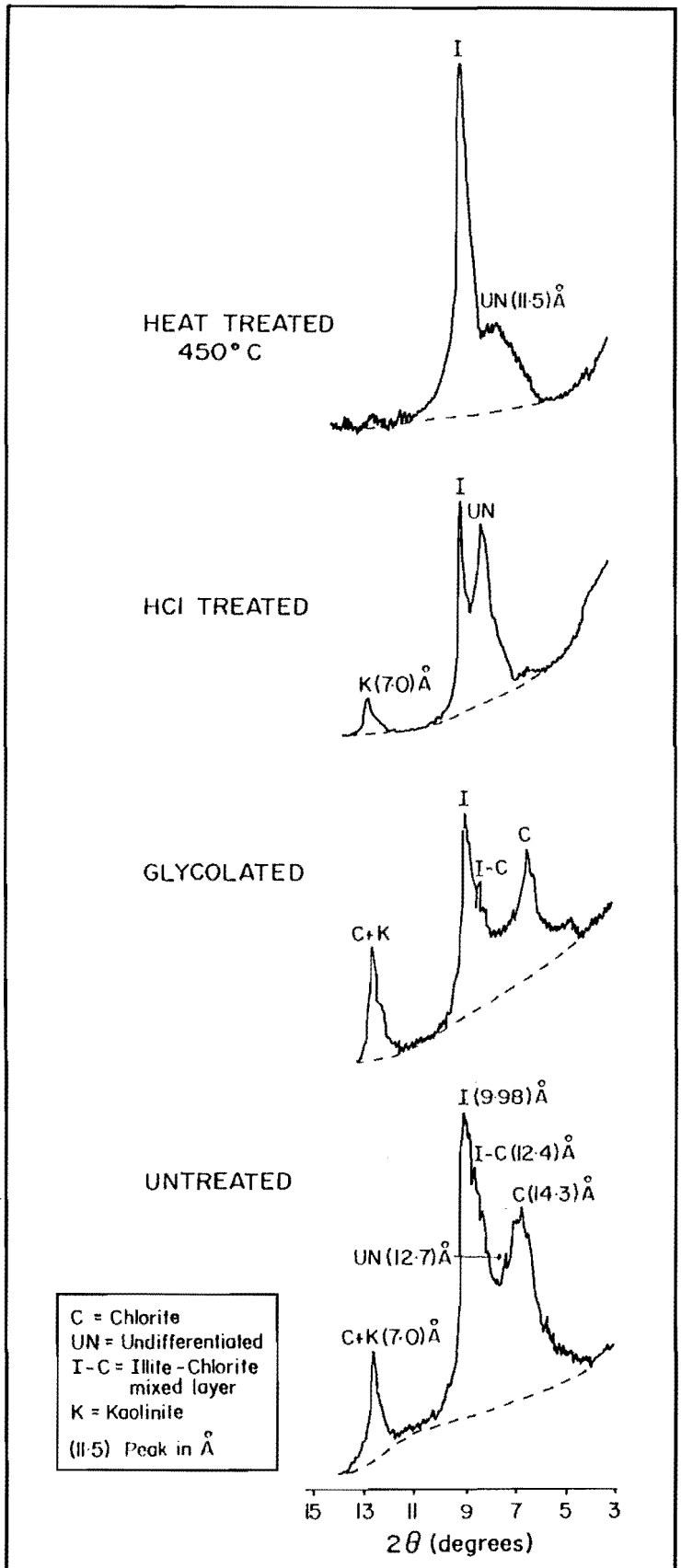


Figure A11.2 XRD - Diffraction patterns of natural soil in response to various treatments

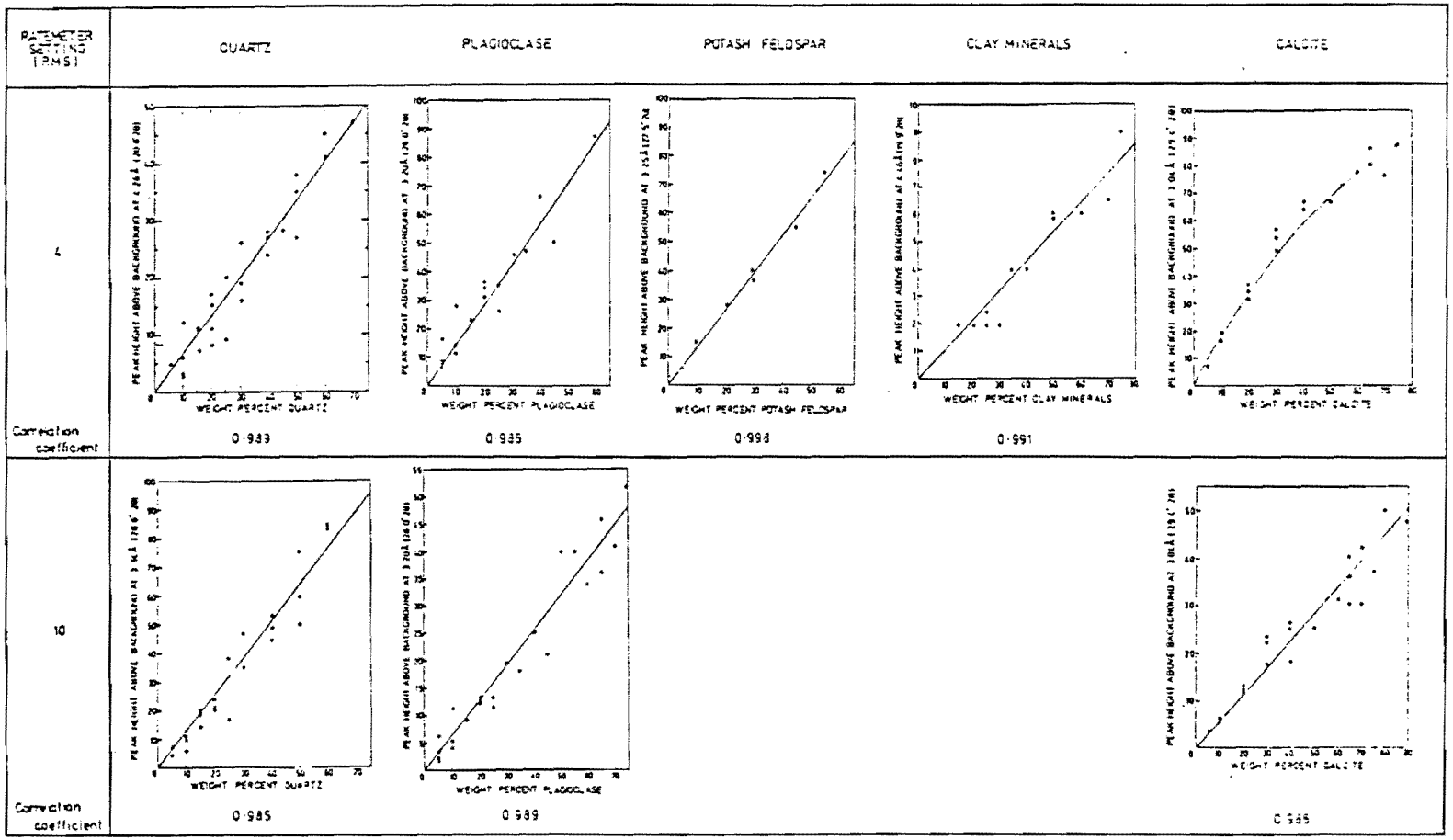


FIG. A11.3 XRD intensity-concentration plots for quartz, plagioclase feldspar, potash feldspar, clay minerals, and calcite at rate meter settings of 4 and 10. Linear correlation coefficients are at the 95% significance level. (from Nelson & Cochrane, 1970)

2) The refracting ability of clay minerals of the same species, which is dependent on composition and degree of crystallinity, is considered to be constant.

3) The weighting corrections selected for individual clay mineral species are assumed to be valid.

Symbols U, G, H and HCl refer to untreated, glycolated, heat and HCl treated samples respectively. The calculation procedure is as follow;

1) ON the X-Ray diffractogram pattern of untreated sample, the peak heights of 3.3 Å illite and 3.5 Å kaolinite and chlorite above background were measured and peaks were compared directly.

2) On the X-Ray diffractogram of the glycolated sample, the peak heights 17 Å smectite, 10 Å illite, 11 Å (illite-smectite), 12-13 Å (undifferentiated mixed-layer clay) and 14 Å (illite -chlorite-smectite mixed-layer clay) above background were measured. For low angle of polarization the measured peak heights need correction and are divided as follows:

Peaks at 17 Å by 4, and 11 Å , 12-13 Å and 14 Å by 2. The corrected peak intensities are then divided by the 10 Å peak height of illite and summed along with the value of (C+K) which achieved in step 1 and recalculated to 100% .

3) On the diffractogram pattern of HCl treatment samples the peak height of 10 Å illite and 7 Å kaolinite were measured. then the peak height value for 7Å kaolinite divided by a factor of 2, and compared to the 10 Å peak height of illite. This ratio is then multiplied by percentage of illite achieved in step 3.

Calculation

1) illite 3.3 Å = 9.6 cm
kaolinite 3.5 Å = 4.2 cm
and C+K = 3.5 Å / 3.3 Å
= 4.2 cm / 9.6 cm = 0.43

2) 10 Å illite = 8.3 cm
14 Å chlorite = 5.5cm
12-13 Å illite - chlorite mixed layer = 5.0 cm
12-13 Å Undifferentiated mixed layer = 2.1 cm
12-13 Å I-C = 5/2 = 2.5 cm
12-13 Å Undifferentiated (UN) = 2.1/ 2 = 1.05

I-C = 2.5 / 8.3 = 0.3
UN = 1.05 / 8.3 = 0.126
C+K = 4.2 / 9.6 = 0.43
I = 8.3 / 8.3 = 1.0
Total = 1.856
Therefore;
I-C = 0.3 / 1.856 x 100 = 16%
UN = 0.126 / 1.856 x 100 = 7%
C+K = 0.43 / 1.856 x 100 = 23%
I = 1 / 1.856 x 100 = 54%

3) K = 7 Å HCl / 10 Å HCl x illite% / 2
K = 1.4 / 8.6 x 54 / 2 = 4.0%
C = (C+K) - K% = 23 - 4 = 19%

APPENDIX: 12 SEM ANALYSES

Sample Preparation

a) Bulk Fraction

Air dried crumbs of natural and stabilised soil (3 x 3 mm in size) were mounted on SEM aluminum stubs using Araldite. The sample were then left to air dry for 24 hours, after which a thin coating (200 Å - 500 Å) gold- palladium was applied.

b) Clay Fraction

A 1% clay suspension was prepared as described in the procedure for clay separation (section A11.2). The diluted clay suspension was the placed on a cover slip (mounted on an aluminum stub) and left to air dry, for 24 hours. The air dried samples were then coated with gold-palladium.